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NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

**AN ASSESSMENT OF HYDROGEN AS A MEANS TO
IMPLEMENT THE UNITED STATES NAVY'S
RENEWABLE ENERGY INITIATIVE**

by

Jason D. Paradis

September 2014

Thesis Advisor:
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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE September 2014	3. REPORT TYPE AND DATES COVERED Master's Thesis	
4. TITLE AND SUBTITLE AN ASSESSMENT OF HYDROGEN AS A MEANS TO IMPLEMENT THE UNITED STATES NAVY'S RENEWABLE ENERGY INITIATIVE			5. FUNDING NUMBERS	
6. AUTHOR(S) Jason D. Paradis				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES) N/A			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. IRB Protocol number ____N/A____.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (maximum 200 words) In response to Presidential Executive Order 13514, the Secretary of the Navy established the 1GW Task Force to meet the Navy's goal of producing at least half of shore-based energy requirements from alternative energy sources. In this thesis, the question is investigated whether renewably produced hydrogen can contribute to the accomplishment of this goal. It is known that ocean wind energy has yet to be fully exploited as a renewable energy source. It is therefore proposed to use sailing ships equipped with hydroturbines and electrolyzers to convert this ocean wind energy into storable energy in the form of hydrogen. The hydrogen is then compressed and transported to nearby naval facilities. The technical and economic aspects of this "energy-ship" concept are analyzed by estimating the drag of the sailing ships, sail lift, and the power requirements of the desalinators, electrolyser, and hydrogen compressor. A previous study of the power requirements of the 76 inhabitants of Grimsey Island, near Iceland, is used to compare the "energy-ship" power production method with wind turbine based hydrogen production. It is found that 13 Catalina 36 sized, autonomously operating, sailboats can provide the Grimsey Island power at an economically competitive cost with the previously proposed wind-hydrogen method.				
14. SUBJECT TERMS hydrogen, energy-ship, renewable energy			15. NUMBER OF PAGES 93	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UU	

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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**AN ASSESSMENT OF HYDROGEN AS A MEANS TO IMPLEMENT THE
UNITED STATES NAVY'S RENEWABLE ENERGY INITIATIVE**

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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ABSTRACT

In response to Presidential Executive Order 13514, the Secretary of the Navy established the 1GW Task Force to meet the Navy's goal of producing at least half of shore-based energy requirements from alternative energy sources. In this thesis, the question is investigated whether renewably produced hydrogen can contribute to the accomplishment of this goal. It is known that ocean wind energy has yet to be fully exploited as a renewable energy source. It is therefore proposed to use sailing ships equipped with hydroturbines and electrolyzers to convert this ocean wind energy into storable energy in the form of hydrogen. The hydrogen is then compressed and transported to nearby naval facilities.

The technical and economic aspects of this "energy-ship" concept are analyzed by estimating the drag of the sailing ships, sail lift, and the power requirements of the desalinators, electrolyzers, and hydrogen compressors. A previous study of the power requirements of the 76 inhabitants of Grimsey Island, near Iceland, is used to compare the "energy-ship" power production method with wind turbine based hydrogen production. It is found that 13 Catalina 36-sized, autonomously operating, sailboats can provide the Grimsey Island power at an economically competitive cost with the previously proposed wind-hydrogen method.

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ACKNOWLEDGMENTS

I would like to give special thanks to Professor Emeritus Maximilian Platzer for his dedication to this project and continued support throughout this endeavor

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I. INTRODUCTION

In 1975, Wallace Broecker stated that the Earth's then-current natural cooling period would soon no longer be able to neutralize the heating effect from trapped CO₂ gas in the atmosphere due to the burning of fossil fuels, and predicted that we would enter into a period of global warming that could have catastrophic effects [1]. Since the term global warming was coined in 1975, international government agencies and various scientific communities have continued to conduct research in order to establish to what degree the burning of carbon-based fuels has affected the environment and to determine if any measures can be taken that will negate or reverse the negative effects associated with the use of fossil fuels.

Global warming and the adverse effects associated with a global climate change affect every aspect of life on the planet. Research has been conducted that shows that a global rise in the average surface temperature of the planet can adversely affect food security, availability of freshwater, habitable land mass and drastically shift the current social and economic status quo both locally and internationally. The data in Figure 1 is based on specific representative concentration pathways (RCP). The RCPs are derived from different emission scenarios that describe and predict future releases of greenhouse gases and other pollutants into the atmosphere. According to the IPCC, “[t]hey are consistent sets of projections of only the components of radiative forcing (the change in the balance between incoming and outgoing radiation to the atmosphere caused primarily by changes in atmospheric composition) that are meant to serve as input for climate [modeling]” [2]. As shown in Figure 1, regardless of whether a conservative model is used to forecast the global average surface temperature change of the Earth, an increase in the average surface temperature is predicted. Whether this trend levels out or continues to rise over the next 50 years is still unclear, but it is clear the average surface temperature will increase based on current temperatures.

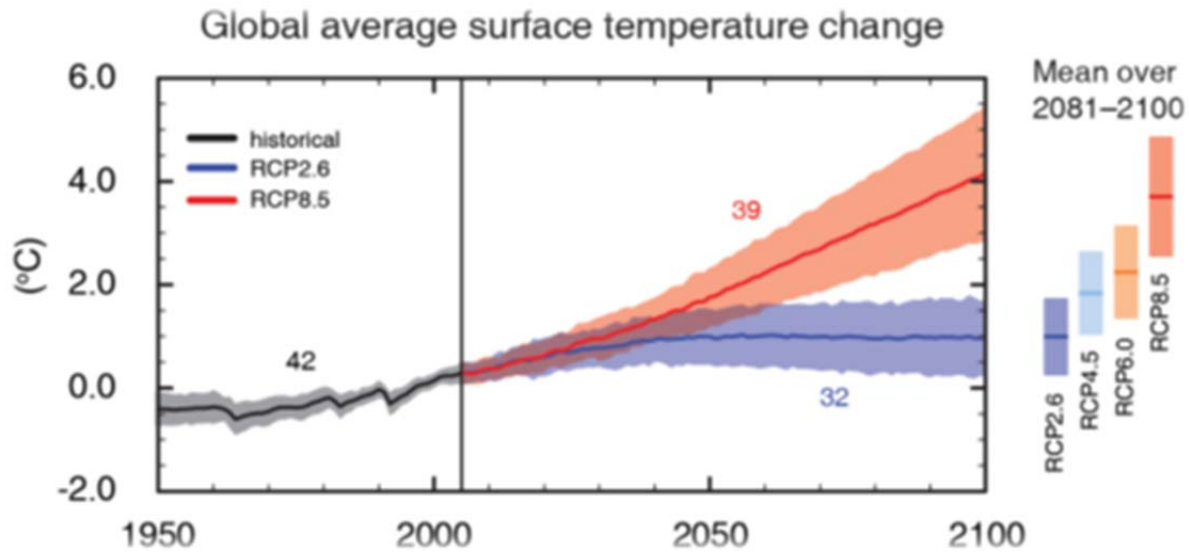


Figure 1. Global Average Surface Temperature Change, after [3]

Although food shortage is a problem in certain areas of the world there is currently enough food globally produced in order to meet global food demands. There are certain regions in every country that act as that country's breadbasket region or area that produces an agricultural surplus. If the average surface temperature of the Earth increases by only a few degrees Celsius, then these areas could undergo drastic changes and have a substantial negative impact in the region. Based on a report from the IPCC [4], "Climate-related disasters are among the main drivers of food insecurity, both in the aftermath of a disaster and in the long run." Since over 70 percent of agriculture is rain fed, it is reasonable to infer that a country's food security is highly sensitive to changes in rainfall, which would imply that food security is most adversely affected by droughts or flooding [4].

Global fisheries are another industry that are being affected by global warming and are directly related to food security in many regions around the world, in addition to being related to the gross domestic product of several countries. The IPCC states in a 2014 climate change report [4] that, "[t]he global average consumption of fish and other products from fisheries and aquaculture in 2010 was 18.6 kg per person per year [which was] derived from a total

production of 148.5 million [tons], of which 86% was used for direct human consumption.” It is suggested that an increase in the surface temperature of the ocean may alter the current migratory patterns of certain species of fish in addition to altering the location of current feeding grounds. This will most likely adversely affect some regions while positively affect other regions, but to what extent these effects will have is currently uncertain.

It is certain, however, that global fisheries will all negatively be affected by the increasing pH level of the world’s oceans as carbon based fuels are continued to be used as the primary source of energy. The ocean is vital in helping to reduce and regulate the amount of carbon dioxide that is in the atmosphere. The ocean is continually absorbing carbon dioxide, but as it continues to absorb larger amounts of carbon dioxide the pH is beginning to decrease and the ocean is becoming more acidic. This trend is being amplified by the increasing average surface temperature of the ocean. The increasing surface temperature is making it more difficult for the ocean’s natural circulation to exchange nutrient rich deep water for the nutrient depleted surface waters. This may lead to stratification of the ocean which will accelerate the acidification of the surface layer and drastically reduce the amount of carbon dioxide that the ocean will be able to absorb [5], [6].

When the ocean absorbs carbon dioxide it reacts with sea water producing carbonic acid [6]. The formation of carbonic acid can be measured by tracking the pH of the ocean. The rising amount of carbon dioxide and the lowering pH of the ocean are shown in Figure 2. The pH associated with typical items found in the average household are shown in Figure 3 in addition to the pH values associated with acid rain and the point at which fish reproduction is negatively impacted.

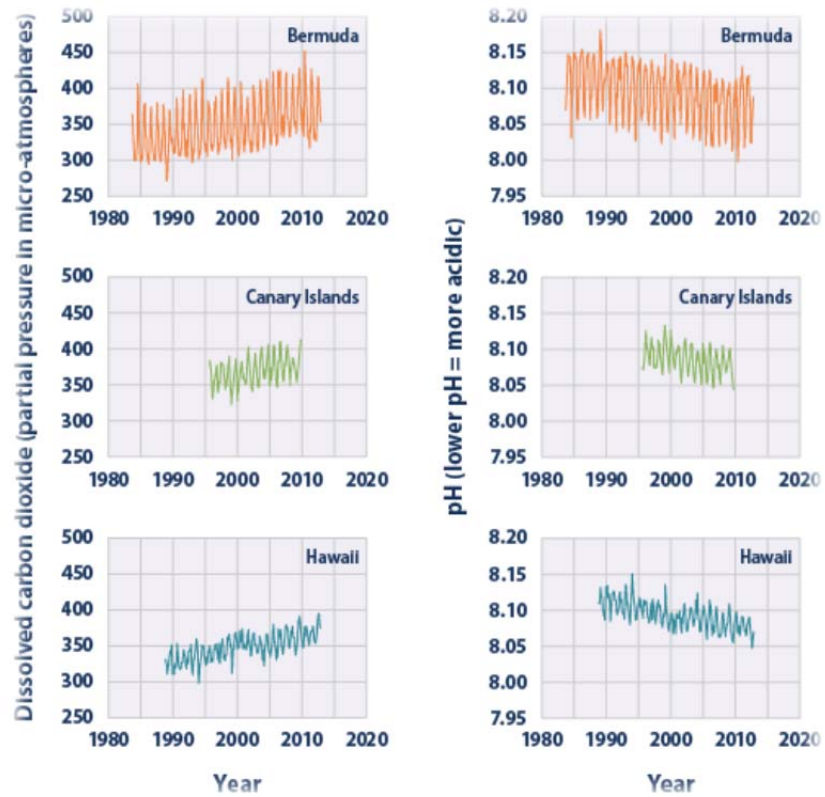


Figure 2. Changes in Dissolved Carbon Dioxide Levels and Ocean pH, after [5]

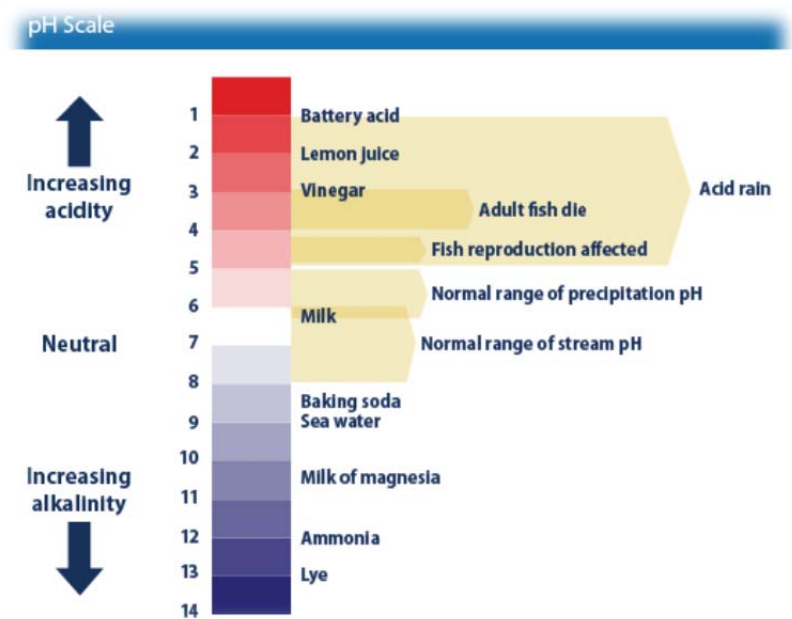


Figure 3. pH of Household Items and Associated Effect on Fish, after [5]

As the world's average surface temperature increases and continues to negatively impact global food security it also adversely affects global freshwater supplies. The effect of flooding and drought on food security in an area has already been discussed, but they can also affect the quality of the freshwater supply in that region. Both flooding and drought can affect a freshwater supply which can adversely affect the water quality and make it unhealthy for humans to drink. Flooding is associated with runoff which can carry pollutants and harmful chemicals into local freshwater supplies, but drought has a similar effect. As the water level in a lake or river begins to decrease, the concentrations of dissolved solids in the water increase and can lead to re-suspension of bottom sediments having negative effects on the quality of the water supply [7].

Flooding and drought are not the only natural disasters that can affect the world's freshwater supply. A large percentage of the global population depends on the slow melting of seasonal snow packs and glaciers to refill and feed their fresh water supply. Increasing average global temperature is being linked to trends that indicate that these snow packs are forming later in the winter season and subsequently melting earlier. The decreased volume of these snow packs, in addition to the earlier melting time, is causing freshwater shortages throughout the year when precipitation is minimal [8].

Flooding can occur in areas whose freshwater supply is fed from the slow melting of glaciers when they begin to melt too rapidly. This adversely affects the quality of the freshwater supply in addition to the habitability of the land in that region. The habitability of an area can also be affected by an increase in the world's ocean level which is caused from melting of polar ice in addition to the thermal expansion of ocean water due to the increase in the average ocean surface temperature.

It is possible that the world will experience a two hundred millimeter (0.6562 feet) increase in the average ocean level by the year 2060 as shown in Figure 4. This will have devastating consequences for low-lying coastal areas

such as Florida, which has 4,500 square miles of land within 4.5 feet of sea level, an area larger than the state of Delaware [9].

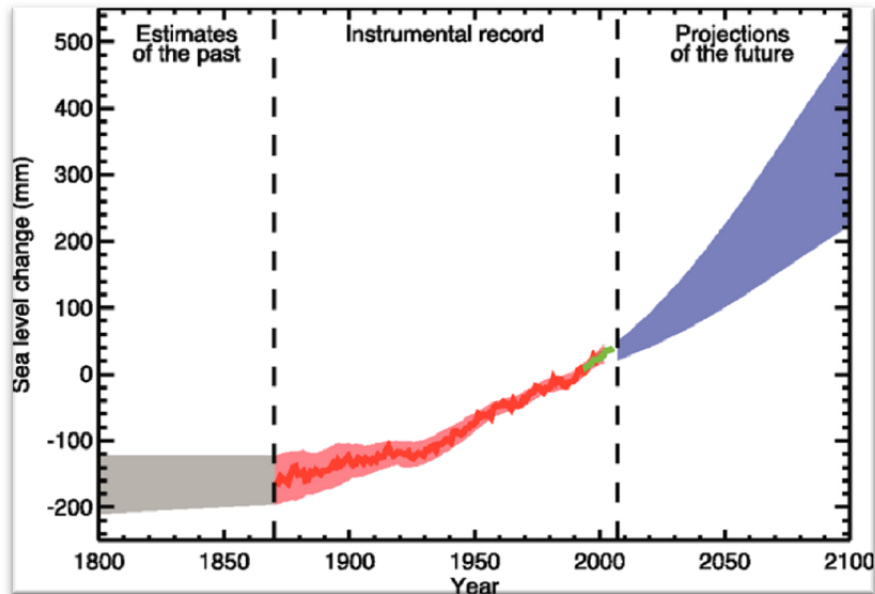


Figure 4. Historical and Predicted Sea Level Change, after [10]

Changes in any country's access to food, freshwater, or habitable land mass can have significant impacts on that country's status in the international community both socially and economically. It is for these reasons that the United States and the rest of the international community have to aggressively pursue alternate energy sources in order to reduce the reliance on carbon-based fuel sources. Research suggests that the power generated from all currently available renewable energy sources, with the exception of nuclear power, is not enough to meet current or future energy needs. However, it is important to recognize that the wind energy available over the Earth's oceans is not yet being exploited for renewable energy production. In 2009, Platzer and Sarigul-Klijn proposed to use sailing ships together with hydrokinetic power generators to produce electrical power, which in turn is used to split sea water into hydrogen and oxygen [11]. The hydrogen then is compressed and brought back to shore where it can be

reconverted into electricity or used directly for heating and cooking or for transportation in hydrogen-fuel-cell powered vehicles.

It is the purpose of this thesis project to explore the potential of this “energy-ship” concept as a means of contributing to the renewable energy initiative of the United States Navy, outlined in the Navy’s strategy for renewable energy which was promulgated in 2012 [12]. To this end, the question will be investigated whether the power requirements of remote off-grid naval facilities can be met with energy ship supplied hydrogen in place of diesel oil or other fossil-based power generation methods.

Therefore, this report is structured by first documenting the renewable energy initiative, followed by a brief overview of the major hydrogen characteristics and production methods. The fourth chapter contains the description of the energy-ship concept and quantitative estimates of the ship configurations and sizes required to harvest a certain amount of hydrogen. In the fifth chapter this information is used to explore the feasibility of using energy ships to support a remote small naval facility modeled after the power requirements of Grimsey Island. The conclusions and recommendations for future work are summarized in the final sixth chapter.

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II. THE RENEWABLE ENERGY INITIATIVE OF THE UNITED STATES NAVY

In order to address the reality that a global climate change will affect how countries conduct national defense, the United States Navy has taken the initiative to promote the research, development, and the use of renewable energy resources. The United States Navy's renewable energy initiative is an attempt at becoming energy independent and therefore, establishing energy security.

In 2012, Secretary of the Navy, Ray Mabus, established the strategy for renewable energy which outlines the priorities and the general methods in which the Department of the Navy (DON) will achieve energy security. In order to effectively reach the goal of becoming energy independent, the strategy focuses on increasing the use of alternate energy sources in addition to being more energy efficient while continuing to rely on carbon-based fuels throughout the fleet and at ashore facilities.

The United States Navy and Department of Defense (DOD) will continue to improve its energy usage through transparency by conducting audits and reporting its activities pertaining to energy usage. The DON's strategy for renewable energy is derived from several presidential orders for which the DON and the DOD are held accountable to comply with, including Executive Order 13514, Federal Leadership in Environmental, Energy, and Economic Performance, and Title 10 United States Code Chapter 173 on energy security. Both of these documents provide general guidance on mandating the reduction in greenhouse gas emissions, increasing energy efficiency, and by providing specific target percentage reduction goals regarding greenhouse gas emissions.

In order to assist in meeting the requirement set forth in the Presidential and DOD mandates, the DON established the one gigawatt task force. The generation of one gigawatt of renewable energy directly supports the accomplishment of these goals. The Secretary of the Navy has outlined more specific goals for the United States Navy's strategy for renewable energy.

Secretary of the Navy Energy Goals

Energy Efficient Acquisition: Evaluation of energy factors will be mandatory when awarding Department of the Navy contracts for systems and buildings.

Sail the "Great Green Fleet": DoN will demonstrate a Green Strike Group in local operations by 2012 and sail it by 2016.

Reduce Non-Tactical Petroleum Use: By 2015, DoN will reduce petroleum use in the commercial fleet by 50 percent.

Increase Alternative Energy Ashore: By 2020, DoN will produce at least 50 percent of shore-based energy requirements from alternative sources; 50 percent of Navy and Marine Corps installations will be net-zero.

Increase Alternative Energy Use DoN-Wide: By 2020, 50 percent of total energy consumption will come from alternative sources. [13]

Figure 5 shows DON completed renewable energy projects that produce greater than one megawatt of power. It can be seen that the majority of the completed renewable energy projects are photovoltaic. This is consistent with the awarded renewable energy projects shown in Figure 6.

Site	Type	Size (MW)
1. COMPLETED PROJECTS		
Joint Base Pearl Harbor-Hickam, HI	PV	2.3
NAVSTA Norfolk, VA	PV	2.2
NAS Jacksonville, FL	PV	1.3
NAS Corpus Christi, TX	PV	1.2
NAVBASE Coronado, CA	PV	2.7
NAVBASE Ventura Cty, CA	PV	1.4
NAWS China Lake, CA	PV	1.6
SPAWAR San Diego, CA	PV	1.2
MCB Camp Lejeune, NC	PV	2.6
MCRD San Diego, CA	PV	1.7
MCB Camp Pendleton, CA	PV	10
MCAGCC Twentynine Palms, CA	PV	4.6
NSA Souda Bay, Crete	PV	2.0
NAVSTA Guantanamo Bay	PV	1.0
MCLB Barstow, CA	Wind	1.0
NAWS China Lake, CA	Geothermal	170*
Naval Shipyard Norfolk, VA	WTE	40
MCLB Albany, GA	WTE	1.9
MCAS Miramar, CA	WTE	3.2**
Other projects (<1MW):		15.6
Total MW producing:		271

Figure 5. Completed United States Navy Alternate Energy Projects, from [12]

When ranking renewable energy sources it is convenient to examine the power density of a particular type of renewable energy source. Power density can be defined as, “the power per unit area of the power generator or as the power per unit of land or sea area needed to generate this power” [14]. In this case, the power density will be considered as the power per unit of land or sea area needed to generate this power. According to Platzer, photovoltaic cells average about 30 W/m² in the ideal case.

Energy Source	Power Density (W/m ²)
Biomass	0.22
Hydro-Electric	4
Wind Power	5 - 22
Ocean Power (Tidal)	14
Solar (PV)	30
Geothermal	20 -50
Fossil-Based	150
Nuclear	4000

Table 1. Alternative Energy Sources and their Associated Power Densities, from [14]

Although photovoltaic generated power is a start at limiting the production of greenhouse gases it is not a viable option to offering a cost effective alternative to fossil-based fuels. It can be seen from Table 1 that solar power contains only a fifth of the power density compared to fossil-based fuels in the ideal case. From Figure 6 it can be seen that the awarded renewable energy projects still consist mainly of photovoltaic projects, but future planned projects begin to show diversification in the use of other forms of renewable energy. It is calculated that the implementation of the Navy's awarded and planned renewable energy projects will meet the Secretary of the Navy's one gigawatt renewable energy goal, but these projects are location specific and are optimistic. Since a large percentage of the power production anticipated from the

planned renewable energy projects is photovoltaic, there exists the possibility that the DON will not meet its goal of one gigawatt.

Site	Type	Size (MW)
2. AWARDED PROJECTS		
AUTEC Bahamas	Wind	1
NAVBASE Coronado, CA	PV	1.3
NAWPNSTA Seal Beach, CA	PV	1.9
NAWS China Lake	PV	13.8
MCB Camp Lejeune, NC	PV	8.2
MCB Camp Pendleton, CA	PV	8.1
MCLB Barstow, CA	PV	1.2
MCAS Yuma, AZ	PV	1.5
MCAGCC Twentynine Palms, CA	PV	1.2
Other projects (<1MW):		10.2
Total MW awarded:		48
3. PLANNED PROJECTS		
NAVSTA Rota, Spain	PV	3.6
NAVSTA Rota, Spain (2nd)	PV	2
Hawaii Solar MAC	PV	28+
MCB Hawaii, Kaneohe Bay, HI	Biodiesel	30
JBPHH (Peaker)	Biodiesel	50
JBPHH - West Loch Luahalei EUL	PV	5
JBPHH - Waipio EUL	PV	5
Joint Base Pearl Harbor-Hickam, HI	PV	2.5
PMRF Barking Sands, Kauai, HI	WTE	1.4
NAVSTA Newport, RI	Wind	9
NAVSTA Guantánamo Bay	WTE, PV	10
NAVBASE Ventura Cty, CA	Wind	1.2
NAVBASE San Diego, CA	WTE	20
MCRD San Diego	PV	1.9
NAF El Centro, CA	PV	1
NAF El Centro, CA (exploration)	Geothermal	10-30
NAS Lemoore EJV	PV	60-200
NAWS China Lake (Section 16)	PV	70-100
NAS Fallon, NV (exploration)	Geothermal	10-50
NAS Corpus Christi, TX	PV	1.1
MCLB Albany GA (2nd)	WTE	1.9
MCB Hawaii, Kaneohe Bay, HI	PV	3.3
MCB Camp Lejeune	Bio or PV	25
MCFR New Orleans, LA	PV	2
MCB Camp Pendleton, CA	PV	20-40
MCAS Yuma (Goldwater Range) EUL	PV	100-250
CMAGR Chocolate Mtns, CA	Geothermal	10-30
MCAGCC Twentynine Palms, CA	PV	5-50
MCAS Miramar Landfill (add'l)	WTE	1.5-3
Total MW planned:		485-950
Factored for 24x7 projects' capacity:		820-1500
Factored total for awarded and planned projects:		850-1560MW

Figure 6. Awarded and Planned United States Navy Alternative Energy Projects, from [12]

The DON's planned renewable energy projects are subjected to inconsistencies associated with weather patterns and therefore the generation of one gigawatt of renewable energy could only be accomplished in ideal conditions. In order to guarantee the DON's energy security, a renewable energy source has to be established and implemented that can consistently operate with a high power density. The concept of using hydrogen produced from ocean wind power in the Arctic and Antarctic regions has the potential of being this renewable energy source.

III. HYDROGEN CHARACTERISTICS AND CURRENT HYDROGEN PRODUCTION METHODS

If it is going to be suggested that the United States Navy will be able to use the production of hydrogen in order to meet the Secretary of the Navy's goals regarding renewable energy and to ensure its energy security then it is important to understand what techniques are currently used to produce hydrogen. Hydrogen is designated by the symbol H. It has the atomic number 1, is the lightest element in the periodic table, and has three isotopes: protium, deuterium, and tritium. The density of hydrogen is 0.08988 kg/m³ at 101.325 kPa and 273.15°K (0°C). It is the most abundant element in the universe and was first identified and isolated by H. Cavendish in 1766. At room temperature it is colorless, odorless and not very reactive, unless activated by an appropriate catalyzer, although, at high temperatures hydrogen is highly reactive. Hydrogen is diatomic in its natural state and dissociates into free atoms at high temperatures [15].

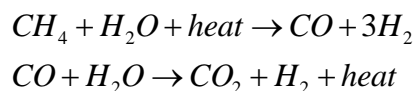
Pure hydrogen does not exist in appreciable amounts. Instead it is always connected to other elements, like carbon in plants, petroleum and natural gas or to oxygen as water. Therefore, an energy source is needed to separate hydrogen from its partner. Hydrogen can be produced from several sources such as natural gas, water, biomass or coal. The energy needed for the production of hydrogen can come from wind, solar, coal, natural gas, or nuclear. As of 2006, 48 billion kilograms of hydrogen were produced worldwide annually, for industrial uses such as ammonia production, petroleum refining, and the processing of metals and food [16].

Several safety concerns exist when handling hydrogen since explosive mixtures are easily formed and it is extremely flammable over a wide range of concentrations. It can also be an explosive hazard if a volume of hydrogen is rapidly depressurized. Hydrogen gas is lighter than air and asphyxiation is a primary health concern due to the potential of oxygen displacement in confined

or poorly ventilated areas. Liquid hydrogen is an extreme cold hazard; therefore, additional safety precautions are taken when working with hydrogen in a liquid state [17].

A. STEAM REFORMING

Hydrogen can be produced from both nonrenewable and renewable sources with steam reforming being the method most currently used. Steam reforming is a technique used to produce hydrogen from a nonrenewable source. Natural gas or a liquid hydrocarbon can be used as a feed stock in steam reforming, but steam methane reforming is the most popular method of producing hydrogen. Complete hydrogen production from steam reforming is accomplished in two stages. Steam reforming of methane is a process that is based on methane reacting with steam in the presence of a catalyst. Nickel is typically used as the catalyst in a reaction that occurs at high temperatures (700°C–1,000°C) and at a relatively low pressure (3–25 bar) [18]. Steam reforming is the first stage of producing hydrogen, but additional hydrogen can be extracted from the steam in a water-gas shift reaction. Steam reforming is an endothermic process that requires heat to be added to the system in order to cause a reaction with the catalyst. The water-gas shift reaction, however, is an exothermic reaction and requires no addition energy to be added to the system for the production of additional hydrogen. Hydrogen production from steam reforming of methane is based on the following reactions



Although steam reforming is a step in reducing global dependence on liquid carbon-based fuels there is a potential problem with this method of hydrogen production. The cost of hydrogen production from steam reforming is dependent on the cost of the feedstock. It has been suggested that the cost of natural gas and methane will remain relatively low and stable until 2025, but

there exist a high degree of uncertainty in forecast models projections beyond this [19]. This implies that the cost of hydrogen production from steam reforming can become relatively expensive and would therefore not be a viable and cost effective alternative to traditional carbon-based fuels.

B. WATER ELECTROLYSIS

The major disadvantage of hydrogen production by steam reforming of natural gas or liquid hydrocarbons is the emission of greenhouse gases. Therefore, the only major hydrogen generation method compatible with the Navy's renewable energy initiative is the electrolysis of water. Electrolysis is used to decompose water into hydrogen and oxygen by passing an electric current through it. William Nicholson and Anthony Carlisle were the first to use electricity for the electrolysis of water in 1800. Zénobe Gramme later developed the process into the first relatively cheap method for the production of hydrogen in 1869.

Electrolysis requires the connection of an electrical power source to two electrodes or two plates, submerged in water, which are typically made from metal such as platinum, stainless steel or indium. The electrodes are labeled as the anode and cathode depending on the chemical reaction that takes place at each site due to the material that is used for each plate. The cathode is negatively charged, causing a reduction reaction, and the anode is positively charged resulting in an anodic reaction. Oxygen is generated at the anode and hydrogen gas is evolved at the cathode due to hydrogen ions gaining electrons [20].

Pure water can be considered a weak electrolyte due its limited ability to auto disassociate. This implies that pure water requires excess electrical energy on order to overcome the activation energy needed to elicit a chemical reaction. The efficiency of this process and rate at which it occurs can be increased by adding an electrolyte, such as a salt, acid or base to the water or being using a nonconsumable electrocatalyst. Strong acids such as sulfuric acid (H_2SO_4) and

strong bases, potassium hydroxide (KOH) or sodium hydroxide (NaOH) are frequently used as electrolytes due to their strong conducting capacities and ability to completely disassociate in water. During the electrolysis of water the number of hydrogen molecules produced is twice the number of oxygen molecules [20], [21].

Alkaline and proton exchange membrane (PEM) electrolyzers are the two main commercially available technologies used to implement water electrolysis. Alkaline electrolyzers require less initial capital investment but are ultimately less efficient than PEM electrolyzers [22]. Since chloride ions are oxidized to chlorine gas as opposed to hydroxide ions being oxidized to oxygen this implies that the electrolysis of sea water produces an unwanted byproduct. The basic principles behind the electrolysis of water and the alkaline and PEM electrolyzers can be seen in Figures 7, 8, and 9, respectively.

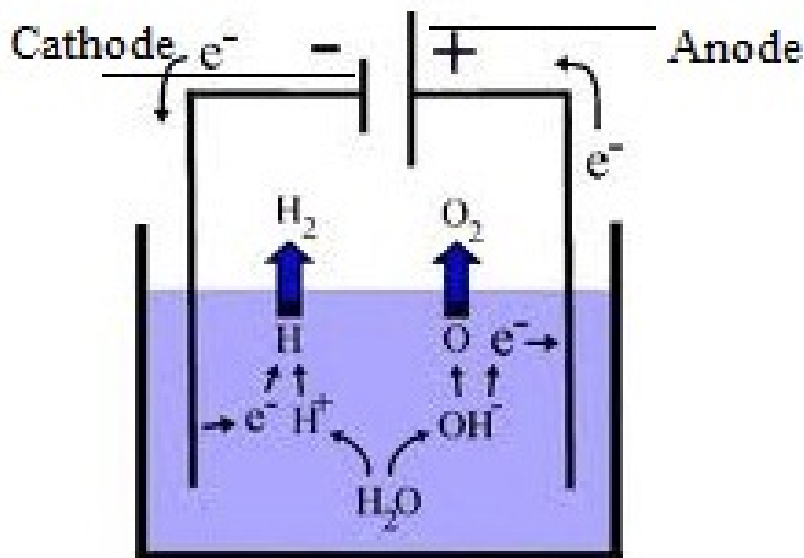


Figure 7. Basic Electrolysis Chemistry, from [23]

Alkaline Electrolyzer Design Basics

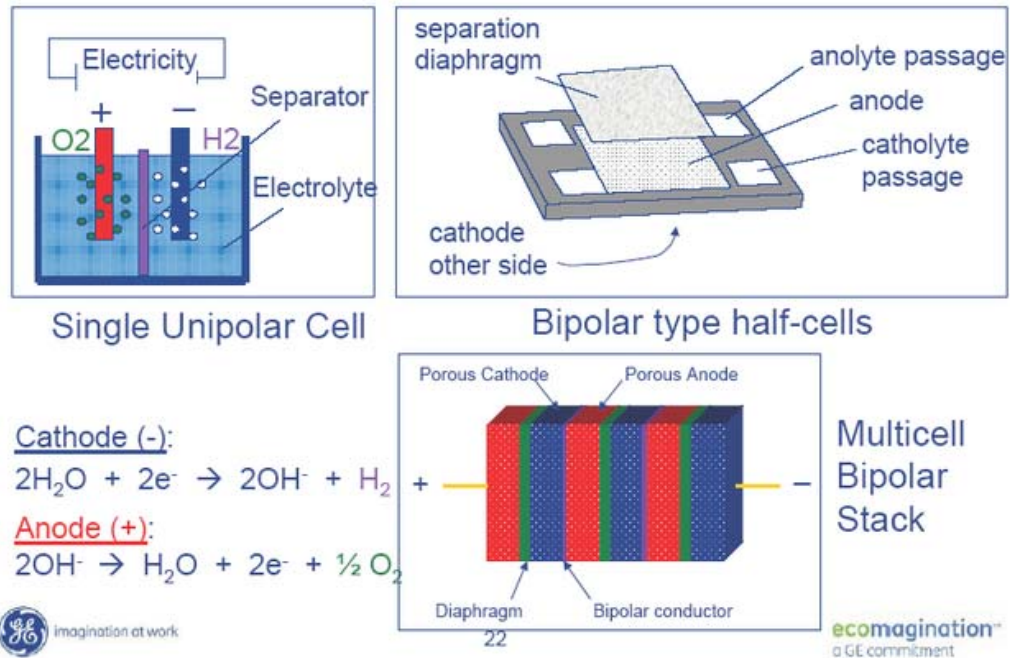


Figure 8. Alkaline Electrolyser Design Basics, from [24]

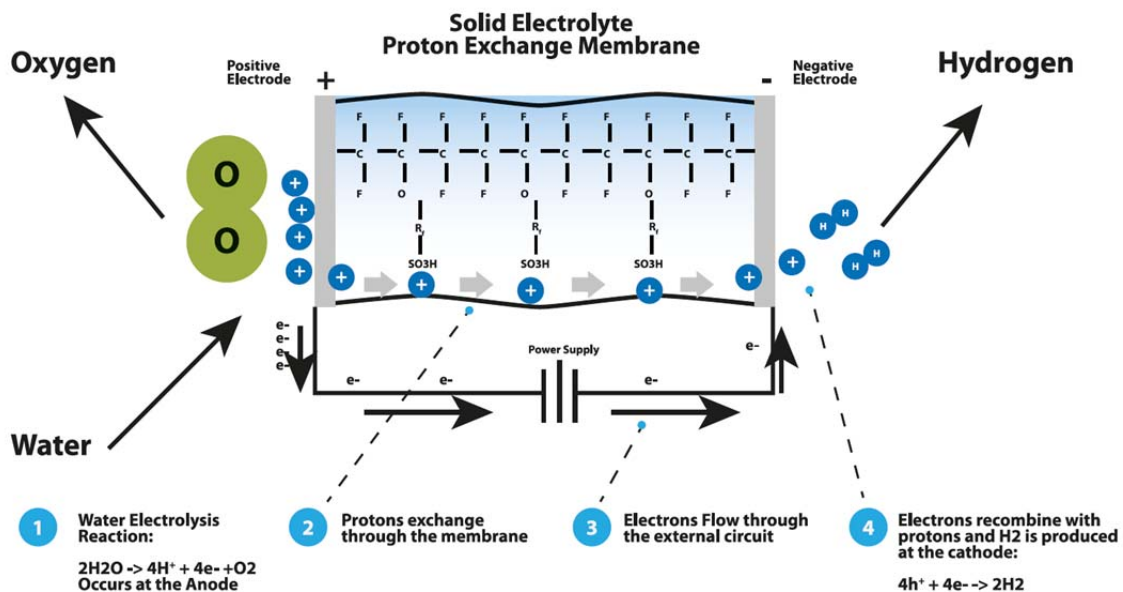


Figure 9. Proton Exchange Membrane Electrolysis, from [25]

C. SEAWATER ELECTROLYSIS

Hydrogen can be produced by using seawater desalination and electrolysis, although direct seawater electrolysis is technically feasible. As previously stated, the biggest problem when using direct salt water electrolysis, in an electrolyser with a high current density, is the creation of chlorine gas at the anode. The evolution of chlorine gas can be minimized by the use of special anode coatings, but the energy requirement of the electrolyser is typically double that required by fresh water electrolyzers. In order to minimize the energy required for the production of hydrogen it is necessary to desalinate the feed water by reverse osmosis prior to electrolysis. Several power conversion components are required in order to execute the energy-ship concept which suggests that weight and size considerations need to be evaluated for design considerations. Reverse osmosis systems, by comparison to other power conversion components, do not require a large area nor are they relatively heavy.

Volume, weight and energy consumption for two reverse osmosis systems from Pure Aqua, Inc. are shown in Table 2.

Generator Power	500 kW	5 MW
Required Fresh Water Flow (m ³ /day)	2.16	21.6
Volume (m ³)	0.21	1.7
Weight (kg)	104	386
Energy Consumption abs (kW)	1.5	7.5
Energy Consumption Relative (%)	0.3	0.15

Table 2. Reverse Osmosis Plant as Specified by Pure Aqua, from [26]

The reverse osmosis cost is very small compared to the other energy conversion equipment cost. According to J. Fournier et al. [27], the specific reverse osmosis cost is approximately \$5.00/kW for electrolysis power inputs of approximately 1 MW and \$9.00/kW for power inputs below 500 kW. Therefore, the desalination power requirement and cost are almost negligible compared to the electrolyser power requirement and cost.

D. ELECTROLYSERS

J. Wong [28] describes an electrolyser that contains two small compressors that produces compressed hydrogen at a pressure of 350 bar. The electrolyzer is manufactured by Stuart Energy Systems and yields approximately 24 kg of hydrogen per day based on a 24-hour operating period.

NEL Hydrogen, a Norwegian company, manufactures the NEL P-60 electrolyser capable of producing 5.4 kg/hr (60 Nm³/hr) of hydrogen at 15 bar from a single electrolyser stack. The NEL P-60 electrolyser is a high-pressure alkaline electrolyser that can be delivered in a 20-foot container or skid-mounted for indoor installation. It is a compact turn-key hydrogen plant that utilizes a 32 percent KOH aqueous solution as its electrolyte. The NEL P-60 uses 4.9 kWh/Nm³ hydrogen produced with an approximate 0.9 L/Nm³ feed water flow rate. The dimensions of the NEL P-60 and skid are 6.1 m x 2.5 m x 2.6 m (LxWxH) and 3.5 m x 2.3 m x 2.2 m (LxWxH), respectively. It also has the unique capability to vary its operating range between 10 percent and 100 percent of its installed hydrogen production capacity [29]. It has been suggested that the acquisition cost of the NEL P-60 electrolyser is roughly \$ 950,000 [30].

The French company, SAGIM S.A., produces the BP-MP 1000/5000 type electrolysers that can deliver 1 to 5 Nm³ or 0.0899 to 0.45 kg of hydrogen per hour at 101.325 kPa, 0°C, and at a maximum output pressure of 10 bar while only requiring 5 kW/Nm³ hydrogen produced. The hydrogen generation units measure 1.950 m x 0.950 m x 2.5m to 4 m and weigh between 1000kg to 2500 kg with a storage capacity of 6 to 24 Nm³ [31], [32].

The HYSTAT 10 electrolyser is capable of producing 8.6 to 21.5kg H₂/day and requires 4.9 kWh per Nm³. It is manufactured by the Canadian company Hydrogenics who are located in Mississauga, Ontario. The HYSTAT 10 system consists of a power/control unit and associated electrolyser. The electrolyser and power/control cabinet measure 1.7m x 1.85m x 2.6m and 1m x 0.5m x 2.1m and weigh 1400kg and 1200kg, respectively [33].

As technologies mature and economies begin to utilize them the price per unit ultimately decreases. According to the DOE 2012 Multi-Year Research, Development and Demonstration Plan the electrolyser system capital cost is \$430 per kW and expected to fall to \$300 by 2015 [34].

E. RENEWABLE ELECTRIC POWER PRODUCTION METHODS

1. SOLAR POWER

Solar power is currently the primary alternate energy source that the Navy is using in order to achieve total energy independence and security. Photovoltaic cells use a process that converts direct sunlight into electricity. Photovoltaic cells are composed of materials that have photoelectric properties. Materials that have photoelectric properties absorb photons and emit free electrons. Initially, photovoltaic cells used silicon, which created an electrical charge when exposed to sunlight, but more recently they use a variety of materials including solar inks, solar dyes, and conductive plastics in order to more efficiently produce an electric change [35].

2. WIND POWER

Wind energy is similar to solar power and other forms of renewable energy in that it is location specific. In order to consistently and cost effectively produce wind energy the wind turbines or wind farms need to be located in an area that experiences a consistent high velocity wind. The energy from wind power is produced when high velocity wind turns the blades of a wind turbine, which spin a shaft connected to an electrical generator [36]. The Navy's "most recent wind

energy system came on line in March 2009 at [the] Marine Corps Logistics Base [in] Barstow, Cali[ornia]. The 1.5 megawatt wind turbine is expected to generate an average of 3,000 megawatt hours of renewable power each year” [37].

3. GEOTHERMAL POWER

The United States Navy has only one geothermal power plant which is located at the Naval Air Weapons Station China Lake. The 270 megawatt geothermal power plant “provides on average 1.4 million megawatt-hours of electricity to the California power grid annually, enough power for 180,000 homes” [38]. Geothermal energy takes advantage of existing underground reservoirs of steam or hot water that are used above ground in order to power a turbine connected to an electrical generator. Flash steam type geothermal power plants are the most common type and operate by using hot water pumped to the surface from underground reservoirs. Some of the hot water flashes to steam as pressure decreases when it is being pumped to the surface. The steam is then used to power a turbine and electrical generator [39].

4. BIOMASS POWER

Biomass power generation is typically associated with biofuels such as ethanol or biodiesel, but it also refers to power generation from municipal solid waste (MSW) or from the use of landfill gas. The DON currently operates a MSW power plant that contributes 1.4 percent of the Navy’s total renewable energy generation in addition to a landfill gas power generation plant that was brought online in 2011 at the Marine Corps Logistics Base in Albany, Georgia. It was estimated to provide an additional 1.9 megawatts of power to the base [40], [41]. A MSW power generation plant generates thermal energy by the burning of landfill waste that produces steam to operate a turbine generator for electrical power generation. Burning MSW produces nitrogen oxides, sulfur dioxide in addition to trace amounts of other toxic pollutants, but does not emit carbon dioxide, the primary greenhouse gas [42]. Biomass power generation from landfill

gas is accomplished by piping methane, a byproduct of landfill decomposition, to a power generating facility where it is burned for electric power generation [41].

5. HYDROELECTRIC POWER

Hydroelectric power generation is similar to wind power generation in that it is based on converting kinetic energy into mechanic power. Hydroelectric power is generated when water from a reservoir falls over a turbine that spins a shaft connected to an electrical generator. Currently the Navy has no completed or planned projects that rely on hydroelectric power generation. Hydroelectric power, as a source of alternate energy, is not anticipated to see much growth in the future based on projections published by the Energy Information Administration. This form of renewable power generation is highly dependent on location and there are only a few areas where hydroelectric power generation can be exploited.

It can be seen from Figures 10–12 that the uses of renewable energy sources are projected to increase in addition to the electricity able to be generated from each source. The electrical power generated by these forms of renewable energy sources can be used in conjunction with a desalinization plant and electrolyser in order to produce hydrogen. The hydrogen can then be stored for use during times when conditions are not conducive for electrical generation.

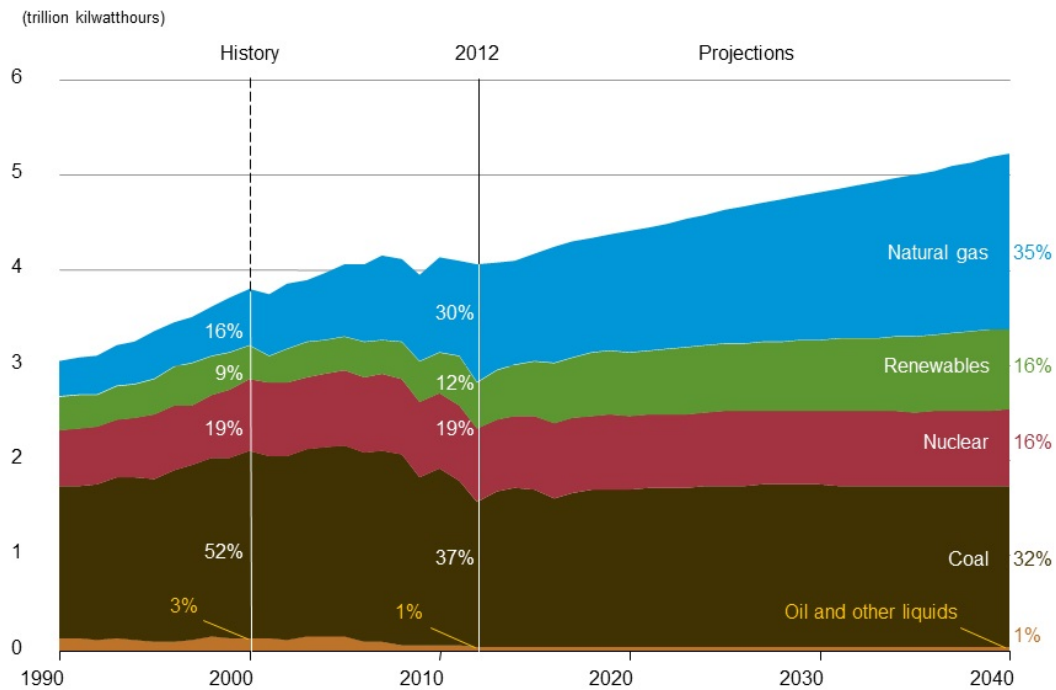


Figure 10. Electricity Generation by Fuel Source, 1990–2040, after [43]

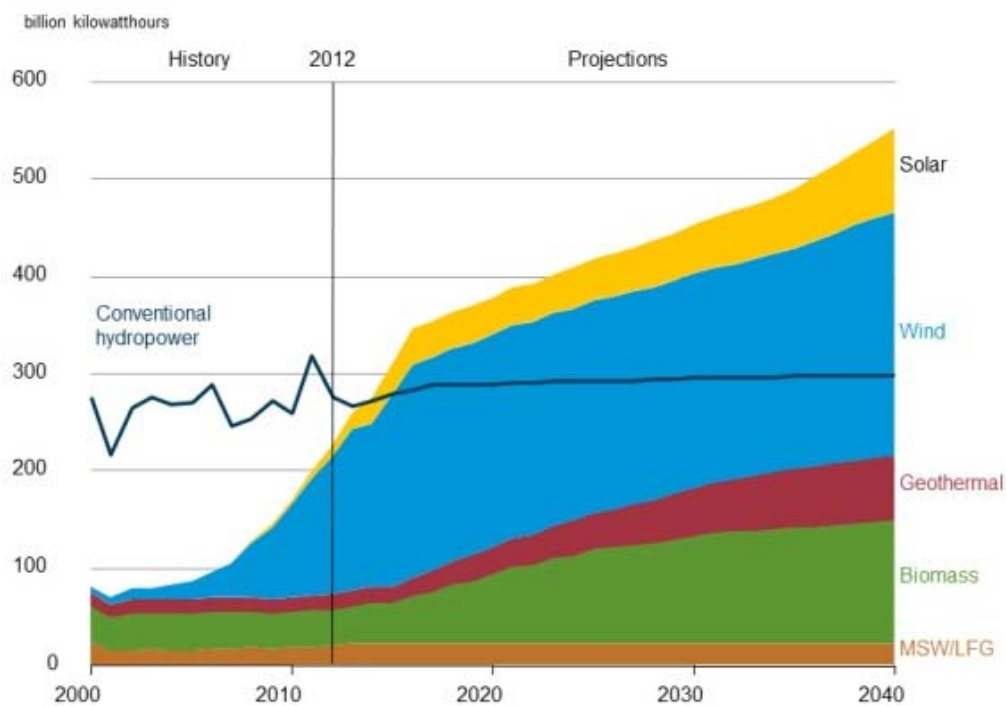


Figure 11. Renewable Electricity Generation Projections by Type, after [43]

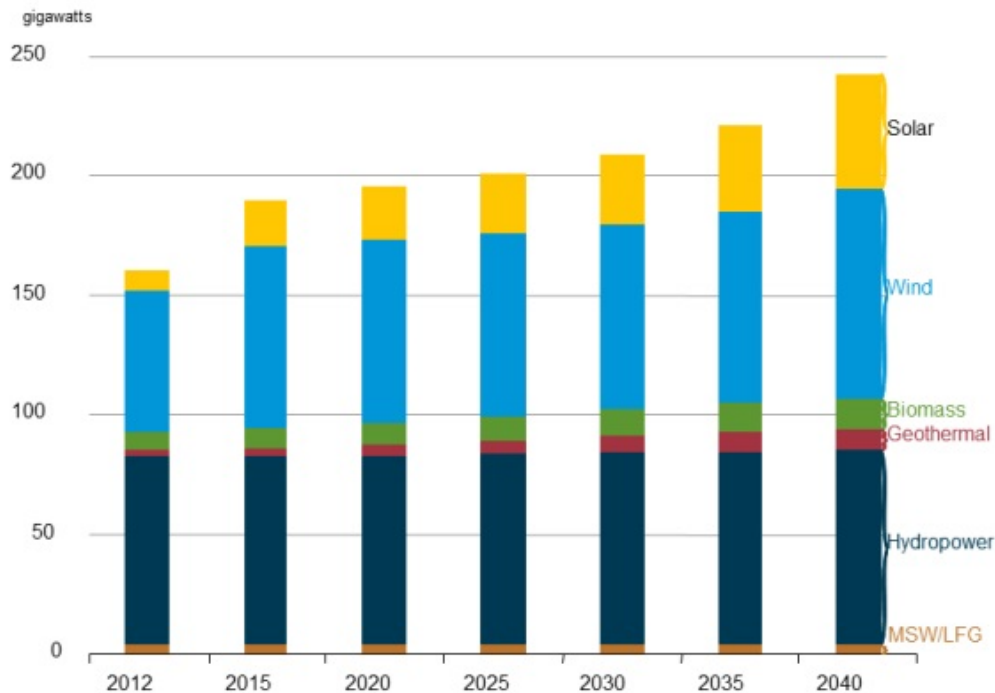


Figure 12. Renewable Electricity Generating Capacity by Energy Source, after [43]

F. HYDROGEN STORAGE

There are many hydrogen storage tanks of different capacities being used for a variety of applications installed all over the world. There are over 100 producers of hydrogen tanks worldwide. However, for transport applications weight and volume need to be minimized, but further technology development of lightweight tanks is still needed. The efficiency of high pressure storage at rated loading is more than 99.9 percent with only minor energy losses due to the eventual venting and purging of the lines [44]. The expected losses are smaller at a lower pressure which implies that the efficiency of high pressure storage is better at partial loading. A hydrogen compressor is usually considered as an auxiliary system and its efficiency is greater than 85 percent with respect to the higher heating value (HHV) [44]. The life of hydrogen tanks is 30 years, but can

often be extended to 60 years with appropriate maintenance. The safety level regarding the storage of pressurized hydrogen is very good, but incidents have occurred mainly due to code violations or disregard of best available practices. Hydrogen leaks from vessels, connections and piping have often been reported, but generally do not cause accidents because hazard review protocols incorporate considerations to avoid such incidents.

Dynetek Industries Ltd. and Quantum Technologies are two of the major suppliers of high pressure hydrogen storage tanks. Dynetek Industries Ltd. is located in California and manufactures the only 70 MPa internationally certified hydrogen storage tank made from high grade aerospace fiber. In 2005, they quoted a storage system cost of \$10/kWh. There are over 1 million high pressure hydrogen storage cylinders in operation worldwide which indicates that the technology is very mature [44]. Although, there is still an increasing need for the development of higher density storage tanks for transportation applications, although, storage tanks at 700 bar made of composite materials are already commercially available.

Although Dynetek Industries Ltd. and Quantum Technologies are not the only two companies that produce hydrogen storage tanks they do make several tanks that are of a size of interest with the appropriate maximum operating pressure. Dynetek Industries Ltd. makes a 350 bar lightweight, aluminum-lined, carbon-fiber-reinforced storage cylinder with a 174 liter water volume. They also supply carbon composite cylinders that are rated to 875 bar and only weigh a third of equivalently sized steel cylinders [28]. For the energy-ship design it is critical to maximize the storage capability of the hydrogen storage tank while minimizing the weight and size. Dynetek model W290 tanks weigh only 121kg and can store 80kg of hydrogen at 250 bar. They have a water volume of 290 liters and measure 2.88 m with a 0.416 m in diameter [28]. Quantum Technologies' Type IV H₂ cylinder weighs 20kg and can store 1.55 kg of hydrogen at 350 bar. It has a water volume of 40 liters and measures 0.94m with a diameter of 0.274m [45]. Both small and large volume hydrogen cylinders have

to be considered for the energy-ship concept. The hydrogen produced aboard the sailing ships will have to be stored in smaller cylinder and then subsequently delivered to an ashore storage facility that houses significantly larger storage tanks.

The Utsira wind power and hydrogen project designed to supply ten households exclusively by energy generated by wind turbines, which were components of the Norsk-Hydro wind/hydrogen system, used a 2400 Nm³ hydrogen storage tank at 200 bar [46]. During the Grimsey Island study, a 250kg hydrogen storage tank costing \$185,117 was considered for the wind-diesel-hydrogen power generation scenario and an 850kg hydrogen tank costing \$629,399 was considered for the wind-hydrogen scenario. This implies that the storage cost per kg hydrogen was approximately \$ 740/kg [47].

G. HYDROGEN COMPRESSION TECHNOLOGY

The energy consumption generated by use of a hydrogen compressor needs to be considered in addition to the energy consumption generated from the use of a desalinators and electrolyser as previously discussed. The energy required to compress hydrogen to 350 or 700 bar tank pressure can be estimated from thermodynamic principles. The specific energy consumption required to compress hydrogen from an initial pressure of 30 bar to a final pressure of 350 bar and 700 bar is 2500 Wh/m³ and 3500 Wh/ m³ H₂, respectively. This energy consumption can be reduced by approximately 50 percent by the use of a H₂ Nitridor booster [27]. RIX Industries, located in Benicia, California, in addition to other manufactures offers several oil-free hydrogen compressors over a wide range of hydrogen flow rates.

IV. THE ENERGY SHIP CONCEPT

A. BASIC CONSIDERATIONS

In their book “Aerohydronautical Power Engineering” M.F. Platzer and N. Sarigul-Klijn [14] emphasize that the various renewable energy sources currently available for exploitation have much smaller energy or power densities than nuclear or carbon-based power sources such as coal, oil, and natural gas.. Consequently, the amount of land needed to produce an equivalent amount of power is imposing a genuine restraint on the development of renewable power production methods. Indeed, most analysts project that only a partial transition to renewable power will be possible by the end of the century. For example, D.J. MacKay [48] in his book “Sustainable Energy - without the hot air” presents a rather comprehensive analysis of the prospects for renewable power in the United Kingdom and concludes that a complete transition to renewable power without the use of nuclear power is possible only if additional solar power is generated and imported from countries with higher solar power densities, such as North Africa and the Middle East. This would require the development and operation of concentrated solar power plants in these countries and the transmission of power over long distances.

Some ten years ago, a proposal was made to implement this concept in order to make Europe more energy independent from Russia. However, support for this “Desertec Initiative” [49] appears to have been withdrawn in more recent years due to the technical and political difficulties inherent in this concept. M.Z. Jacobson at Stanford University and M.A. Delucchi at the University of California Davis [50] proposed a path to global sustainable energy by 2030 relying entirely on wind, water and solar technologies. Based on projections from the Energy Information Agency (EIA), the world will require 16.9 terawatts of power with the United States requiring approximately 2.8 terawatts. According to Jacobson and Delucchi, the required infrastructure necessary to produce 11.5 TW of renewable energy can be seen in Table 3.

Type of RE Installation	No. of Installations Required	No. Required Currently in Service (%)
Tidal Turbines	490000	< 1
Geothermal Plants	5350	2
Hydroelectric Plants	900	70
Wind Turbines	3800000	1
Wave Converters	720000	< 1
Rooftop PV Systems	1700000000	< 1
Concentrated Solar Power Plants	49000	< 1
PV Power Plants	40000	< 1

Table 3. Required RE Installations Needed to Produce 11.5 TW, from [50]

A point of some interest is to note that half of the nearly 4,000,000 predicted wind turbines that would be required for the production of 11.5TW would be placed off-shore [27]. Jacobson and Archer [51] emphasize that the world's year 2030 projected power demand could be met in excess from wind, but associated restrictions and hurdles from the use of wind turbines are never addressed. These restrictions include limited land space for the placement of wind turbines due to the area being allocated for other uses, noise pollution, and other various environmental and legal constraints. In addition to these constraints, the need for additional infrastructure necessary to transmit the power

generated to the consumer still needs to be addressed. Although it is proposed that wind generated power can meet the current and projected global power demand, energy storage has to be considered during times when there is little to no wind available.

B. GLOBAL WIND RESOURCES

The concept of wind power generation is usually associated with the need for large stationary power plants, thus limiting the use of wind power to land-based wind turbines or to coastal based wind turbines which are firmly anchored to the sea floor. The generation of wind power from land and coastal based platforms severely limits the exploitation of the world's total potential wind energy available. The majority of the global wind power is located over the planet's ocean area which covers 70 percent of the global surface area. W.T. Liu et al [52] calculated and derived the probability distribution and power density of wind speed over the global oceans from QuickSCAT measurements and are shown in Figure 13.

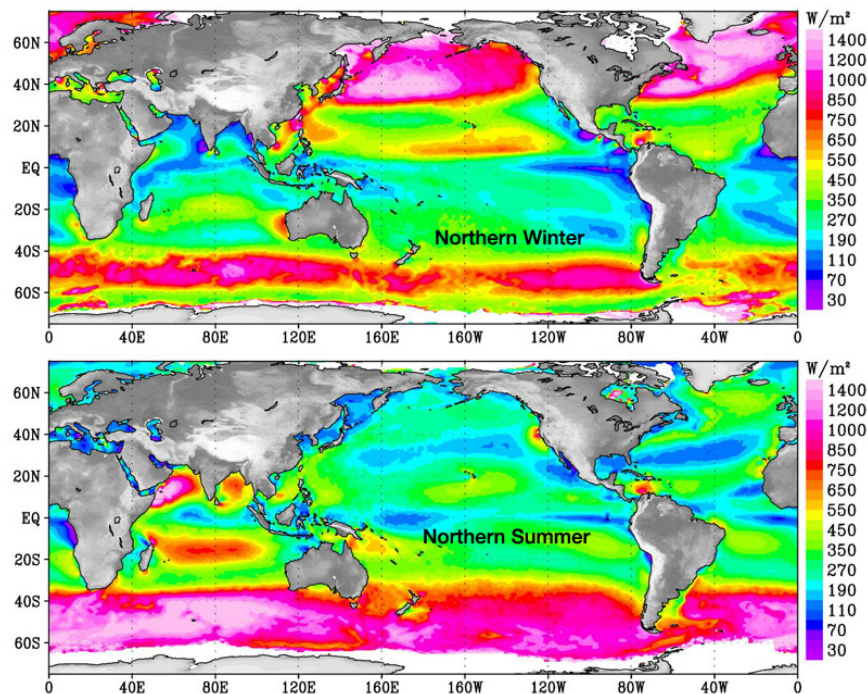


Figure 13. Power Density of Wind Speed Over Global Oceans, from [53]

This data shows that there are regions in the world that maintain a large potential of wind energy and this data is currently being used for the installation of wind farms near coastal regions that exhibit higher potential wind energy. The next logical step is to ask the question whether it is possible to exploit the wind energy available far from coastal regions. As shown in Figure 14 there are vast ocean areas near the Arctic and Antarctica regions with persistently high wind speeds.

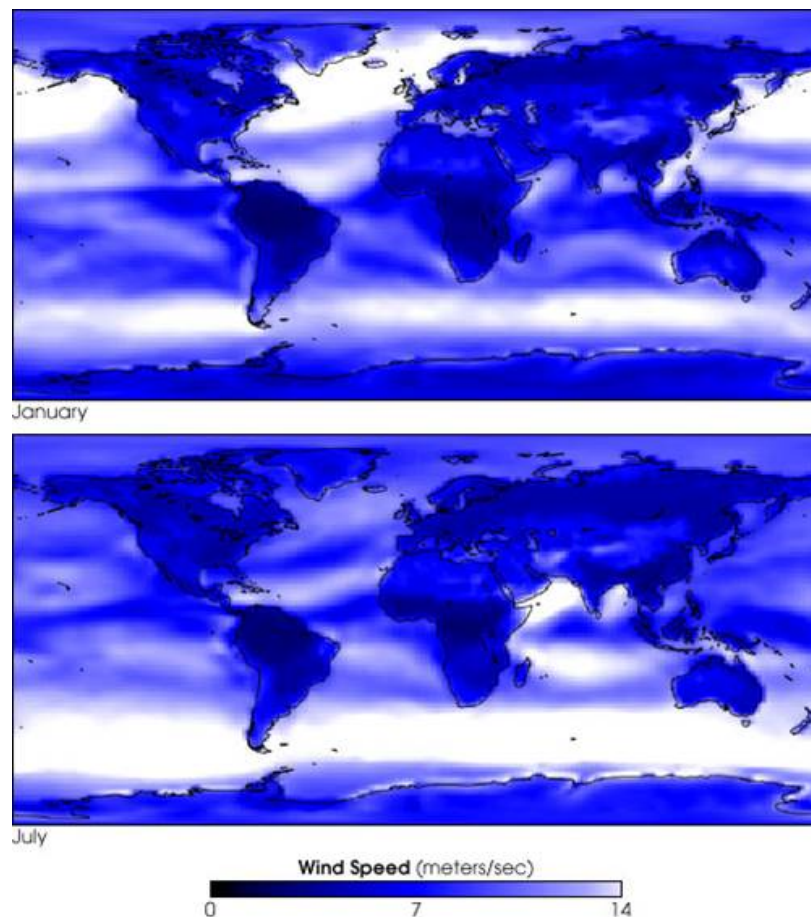


Figure 14. Ocean Surface Wind Speed Distribution, from [14]

Based on the power density of wind speed over the global oceans in addition to global wind speed distribution it is concluded that there is a sufficient amount of renewable energy available in the form of wind power over the oceans to satisfy the current and predicted global energy requirements. The problem of

transitioning to a renewably powered global economy, therefore, is not whether it can be done at all but how to do it in the most effective and rapid manner.

C. ENGINEERING APPROACH TO THE EXPLOITATION OF OCEAN WIND POWER

The extension of the offshore wind farm concept to ocean areas far from coastal regions is unlikely to be practical because of the need to survive severe weather conditions. It is then necessary to abandon the concept of stationary power plants in favor of moving platforms, i.e., ships, which can move away from oncoming storms. The approach has to be to mount hydropower generators on sailing ships in order to take advantage of and derive power from the relative speed between ship and water. In this scenario, ocean winds are used to propel the sailing ship that is equipped with a hydropower generator used to produce electricity. This arrangement is to be preferred over the use of direct wind power generators mounted on floating platforms because hydropower generators are significantly smaller than wind power generators for an equal power output. Modern high-performance sailing ships can reach speeds up to 60 knots (30 m/s); however, the drag induced by a hydroturbine attached to the ship has to be considered. Taking the drag produced by the hydroturbine in consideration there is an opportunity to expose the hydroturbine to consistent water speeds of 5 to 10m/s. This implies that this concept has the potential to harness an energy source superior to other forms of water based renewable energy sources since generated power from the hydroturbine varies proportionally with the third power of the available water speed and Arctic and Antarctic regions experience year-round sustained winds greater than 10m/s. Alternate water based renewable energy sources, such as tidal flow or river in-stream energy conversion, typically experience water velocities between 0.5 to 5 m/s.

As previously discussed, Norsk Hydro [54] established that it is feasible to store electric power output in the form of hydrogen for future use. This was demonstrated during the Utsira wind power and hydrogen project where the output from a 600 kW wind turbine was fed into an electrolyser to generate

hydrogen that was compressed by a 5 kW compressor and stored in a 12 m³ storage tank at 200 bar. The Utsira wind-hydrogen system demonstrated the feasibility of providing ten households with 200 MWh/year. In a similar fashion, the electric power produced by a hydroturbine generator mounted on a sailing ship can be fed into an electrolyser to produce hydrogen and oxygen, which can then be compressed and stored in tanks and later delivered to ashore facilities.

In 2009, these considerations led M.F. Platzer and N. Sarigul-Klijn [11] to propose the use of sailing ships equipped with hydroturbine generators as hydrogen harvesters which could periodically off-load the hydrogen storage tanks to vessels that would transport the hydrogen back to shore for the production of electricity in fuel cells, hydrogen-oxygen power plants, or for heating, cooking or transportation purposes. The concept of the energy ship and the hydrogen generation process is depicted in Figure 15. They refined this proposal in additional papers published in 2010 [55] and 2011 [56].

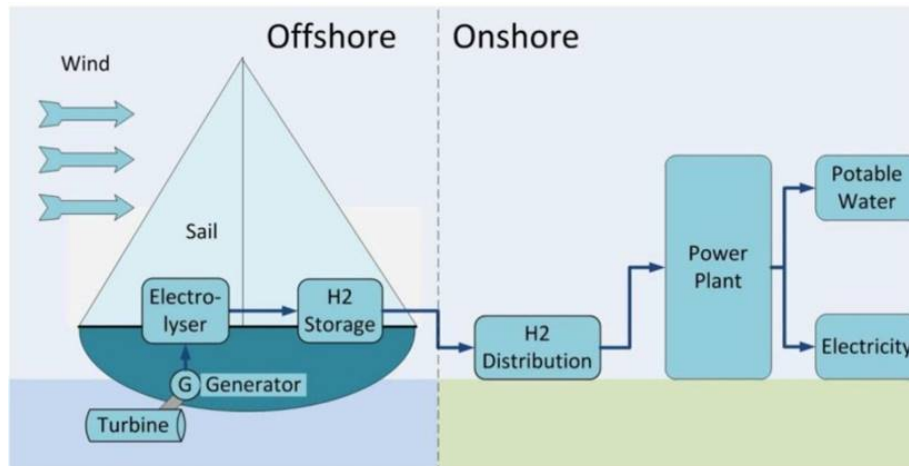


Figure 15. Energy Ship Concept, from [26]

D. SAILING SHIP PERFORMANCE ANALYSIS

An energy ship has to be designed and operated for the specific mission of optimally converting the ocean wind power into mechanical power. In their most recent paper, Platzer et al [26] presented a conceptual design based on

currently available conventional ship design information. Their analysis, therefore, excluded any analysis of hydrofoil boats or other advanced technologies and considered only commonly used single and multi-hull technologies.

For a preliminary analysis, they considered only the force balance and deferred the pitch and roll stability analysis. In order to obtain the sail area required to propel the sailing ship, Platzer et al. estimated the the drag created by the ship and the attached hydropower generators. In their paper on the “Analysis of the Conversion of Ocean Wind Power into Hydrogen,” the viscous drag coefficient of single-hull ships was computed using the formulas [26]

$$\Delta C_f = \left[105 \left(\frac{k_s}{L} \right)^{\frac{1}{3}} - 0.64 \right] \times 10^{-3},$$

where

$$k_s = \text{Roughness of Hull} = 150 \times 10^{-6} \text{ (meters)}$$

$$L = \text{Length of Water Line}$$

It is stated that wave resistance coefficients typically vary between 0.0005 and 0.002 at low Froude numbers for multi-hull vessels and that the total resistance coefficients can therefore, be assumed to vary from 0.004 to 0.008.

Platzer et al. state that “[the] [f]irst estimates of the power and drag of any power extraction device can be obtained from simple momentum theory” [26]. The maximum power extraction occurs when the induced velocity is one third of the inflow velocity. This indicates that power P can be calculated as:

$$Power = P = \frac{A_{Disc} \rho}{2} (V - v)^2 \times 4v$$

where,

$$A_{Disc} = \text{Turbine Disc Area}$$

$$V = \text{Inlet Velocity}$$

$$v = \text{Induced velocity at the turbine disc}$$

and

$$v = \frac{1}{3} V$$

so that the power P is given by

$$P = \frac{16}{27} \frac{\rho}{2} V^3 A_{Disc}$$

and the drag D

$$Drag = D = 2vA_{Disc}\rho(V - v)$$

$$D = \frac{4}{9} A_{Disc}\rho V^2$$

After substitution into the standard drag formula;

$$D = \frac{C_d}{2} \rho V^2 A_{Disc}$$

$$\frac{C_d}{2} \rho V^2 A_{Disc} = A_{Disc}\rho V^2 \frac{4}{9}$$

the drag coefficient becomes

$$C_d = \frac{8}{9}$$

The hydroturbine performance is characterized by the power coefficient,

$$C_p = \frac{P}{\frac{1}{2} \rho V^3 A_{Disc}} = \frac{\text{Rotor power}}{\text{Power in the water}}$$

where the non-dimensional power coefficient represents the fraction of the power in the water extracted by the rotor which implies

$$C_p = \frac{16}{27} = 0.593$$

Therefore, if the dynamic inflow pressure and the disk area are used for non-dimensioning then the power and drag coefficient values are

$$c_p = 0.593$$

$$c_d = \frac{8}{9} \approx 0.8889$$

There is very little experimental information for the power and drag coefficients of hydroturbines and flapping wing power generators, but recently, Bryan et al [57] presented drag and power measurements of the Ampair turbine, Figure 16, and obtained good agreement between their measured drag data and the data published by Ampair.

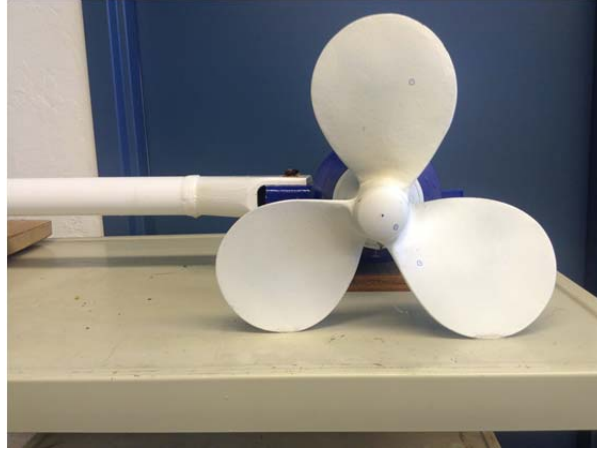


Figure 16. Ampair Hydroturbine, from [57]

However, the power level of the Ampair hydroturbine is very small; less than 100W. Although there is little experimental data regarding the drag coefficient for small flapping-wing generators, Platzer et al. [55] calculated the drag coefficient based on swept area and it was determined that the drag coefficient was approximately 1.1. Due to the lack of data on hydroturbines, Platzer et al. [26] attempted to gain some insight into the feasibility of the energy ship concept by varying the parameters governing power production potential. The major interest during this analysis was the dependence of sail area and hydroturbine size required to generate a specific amounts of power. The results from their parameter sensitivity analysis are shown in Figures 17 to 19. These results were obtained by using the parameters in Table 4.

Power output	1.5MW	Power coefficient	0.6
Wind Speed	10m/s	Power generator drag coefficient	2.5
Sail lift coefficient	1.5	Wetted area	2000 m ²

Table 4. Set of Parameters used for energy Ship Variability Analysis, from [26]

In Figure 17 the effect of ship speed and ship resistance on sail area is depicted. Platzer et al. determined that there is an optimum ship speed between 6 and 8 m/s depending on the chosen ship resistance coefficient. Sail areas below 15,000 m² were considered feasible and were indicated in yellow. The blue line indicated the optimum ship speed at the respective variable setting and was referred to as “Optimized Design Region.” When the ship resistance drag was set to 0.004 it was also determined that a 15,000 m² sail area was required in order to generate 2 MW which is shown in Figure 18. The power generator drag was analyzed in addition to ship resistance drag and the results are shown in Figure 18.

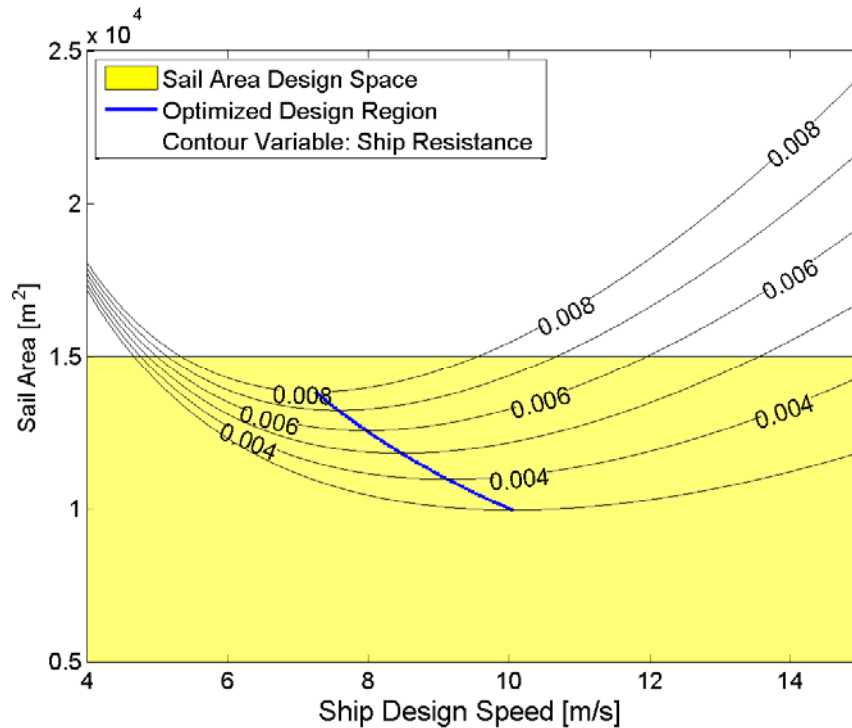


Figure 17. Required Sail Area Varying with Ship Speed and Ship Resistance, from [14]

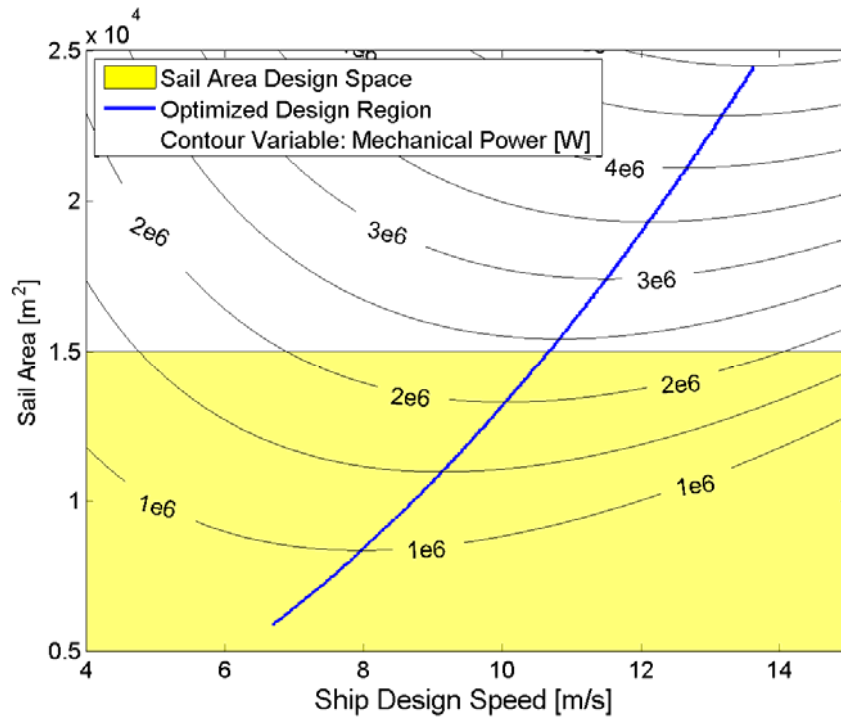


Figure 18. Required Sail Area Varying with Ship Speed and Mechanical Power, from [14]

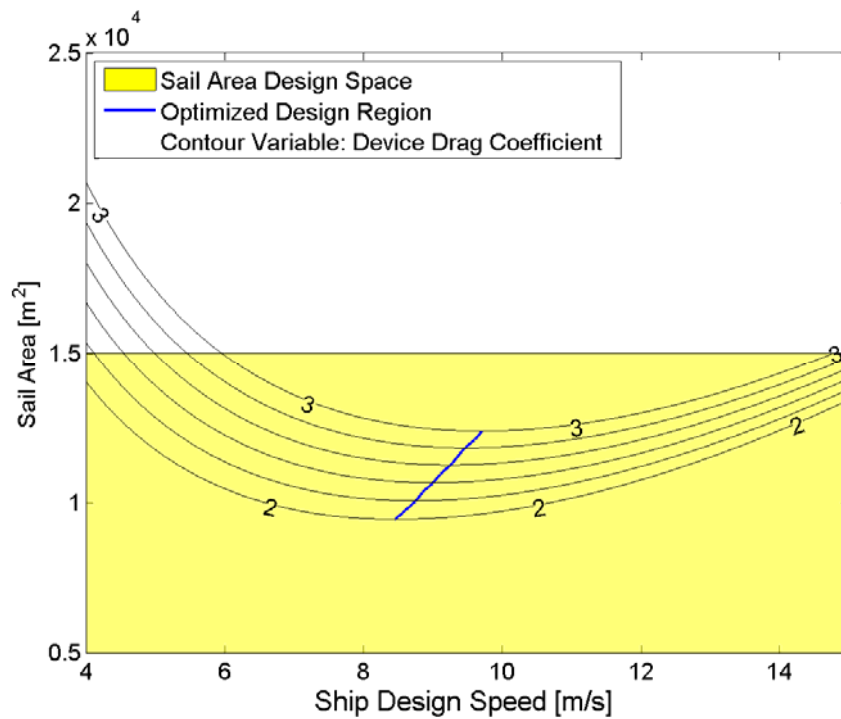


Figure 19. Required Sail Area Varying with Ship Speed and Device Drag coefficient, from [14]

E. UPDATED ENERGY SHIP PERFORMANCE ANALYSIS

The objective of the analysis presented by Platzer et al [56] was to explore the power output which could be obtained from a conventional sailing ship with a sail area of at most 15,000 m². It can be seen from Figures 17 to 19 that a power output of 2 MW can be expected from the parameter variation and for the specific parameter combination shown in Table 4.

Since the design of a vessel with a sail area of 15,000m² is unrealistic, it is of interest to investigate the ship size needed to produce power outputs between 25 to 1000 kW. The analysis was performed using minimum drag ship configurations, such as hydrofoil boats, and updated hydro turbine information obtained from Professor Riedelbauch at the University of Stuttgart [58]. The updated energy ship performance analysis was done utilizing MATLAB. The results of this analysis were obtained by plotting sail area versus ship's speed where sail area was calculated from the equation which can be expressed as thrust equal drag where

$$\text{Total Drag} = D_{Total} = \frac{1}{2} \rho_w V_w^2 C_s A_w + \frac{C_t}{C_p} \cdot \frac{P}{V_w}$$

$$\text{Ship Thrust} = T = \frac{1}{2} \rho_a V_a^2 C_L A_s$$

Solving for sail area yields

$$A_s = \frac{\frac{1}{2} \rho_w V_w^2 C_s A_w + \frac{C_t}{C_p} \frac{P}{V_w}}{\frac{1}{2} \rho_a V_a^2 C_L},$$

where

$$A_s = \text{Ship sail area} \left[m^2 \right]$$

$$\rho_w = \text{Density of sea water} = 1000 \left[\frac{kg}{m^3} \right]$$

$$V_w = \text{Ship speed} \left[\frac{m}{s} \right]$$

$$C_s = \text{Ship drag coefficient}$$

$$A_w = \text{Ship wetted area} \left[m^2 \right]$$

$$C_t = \text{Turbine drag coefficient} = 2.0$$

C_p = Turbine power coefficient = 1.26

P = Power output [W]

ρ_a = Density of air = $1.26 \left[\frac{kg}{m^3} \right]$

V_a = Apparent wind speed $\left[\frac{m}{s} \right]$

C_L = Sail lift coefficient

The results of this analysis are shown in Figures 20 to 25.

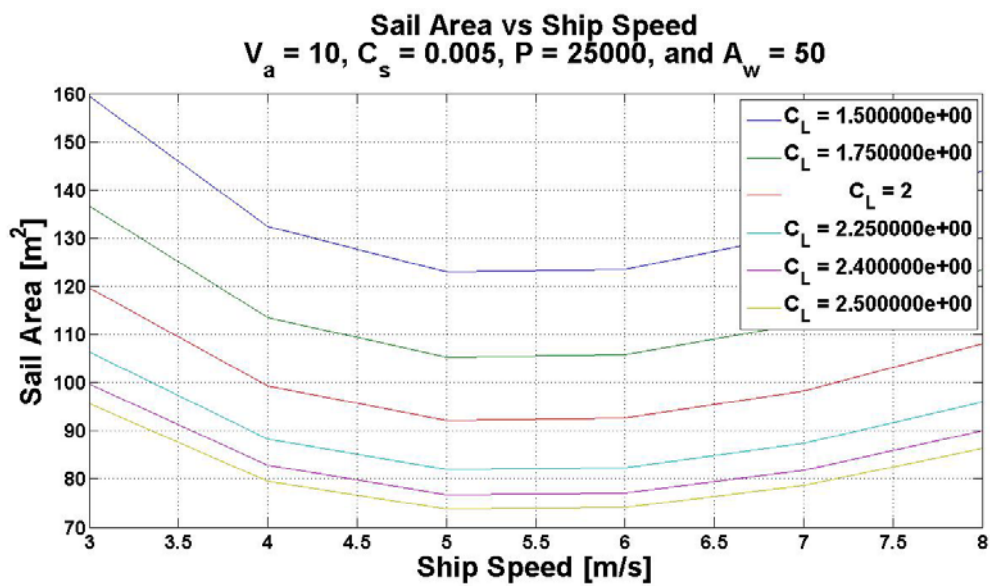


Figure 20. Sail Area versus Ship Speed with Variable Sail Lift Coefficient

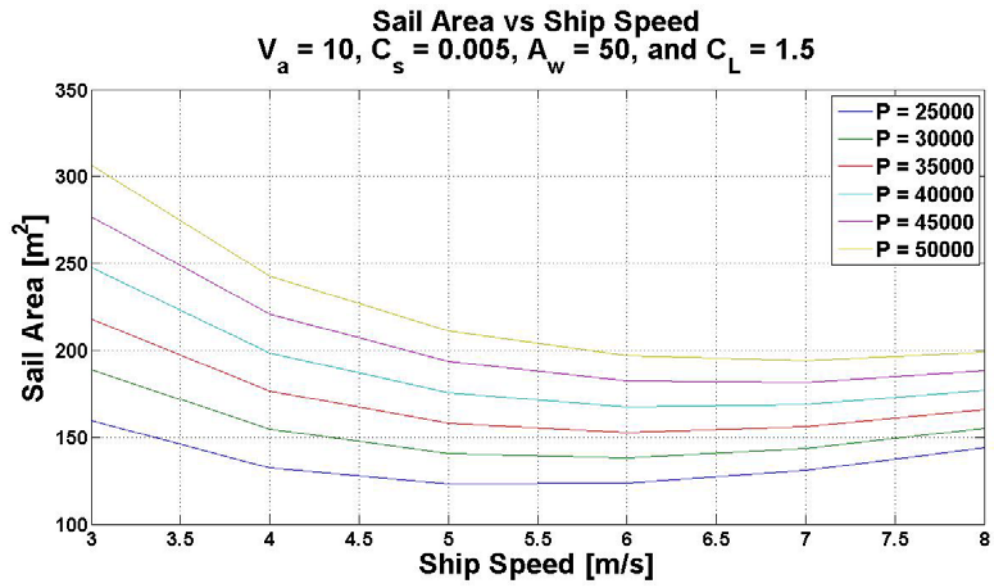


Figure 21. Sail Area versus Ship Speed with Turbine Output Power

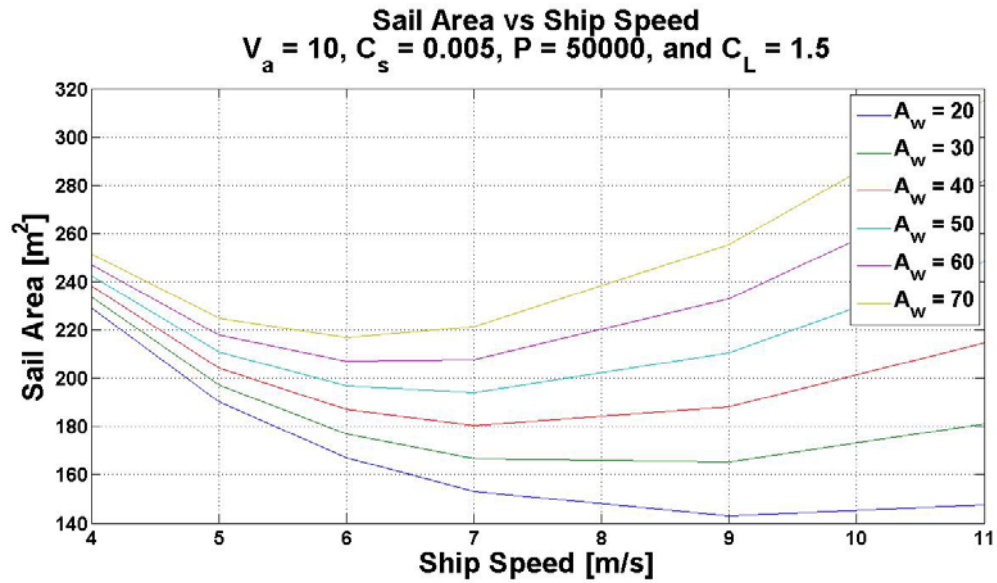


Figure 22. Sail Area versus Ship Speed with Variable Ship Wetted Area

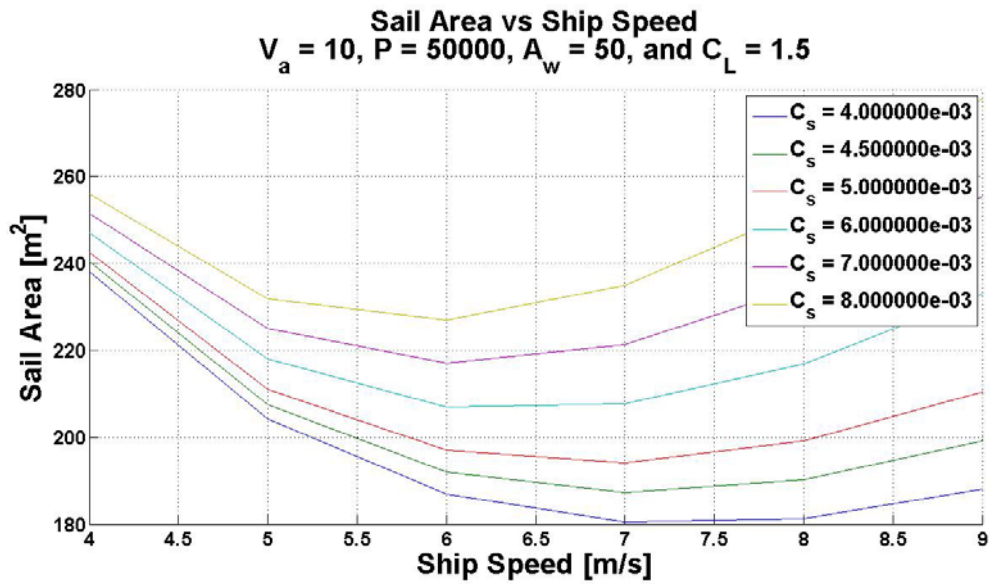


Figure 23. Sail Area versus Ship Speed with Variable Ship Drag Coefficient

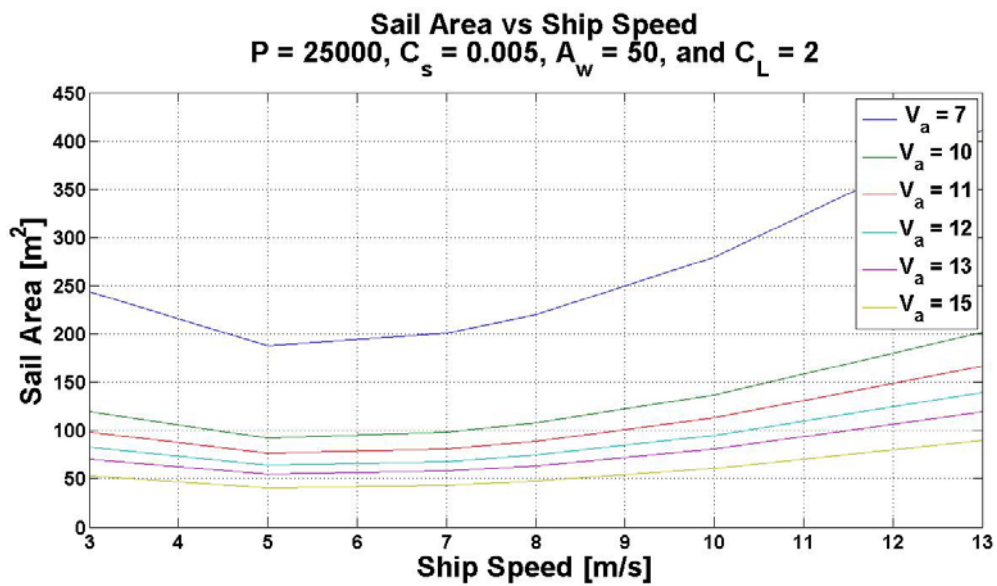


Figure 24. Sail Area versus Ship Speed with Variable Apparent Wind Speed and the Ship Drag Coefficient Set to 0.005

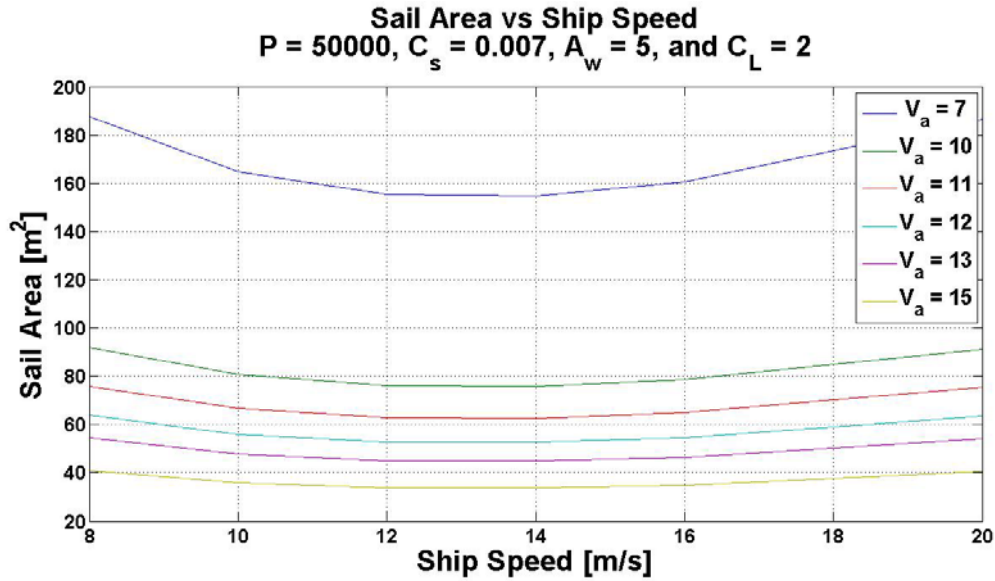


Figure 25. Sail Area versus Ship Speed with Variable Apparent Wind Speed and the Ship Drag Coefficient Set to 0.007

F. PERFORMANCE AND COST ANALYSIS

This analysis reveals that power outputs of 25 kW can be achieved using sailboats that have an approximate sail area of 70 to 90 m². This power output could be accomplished with ship wetted areas of 50 m² such as the Aerodyne 38 shown in Figure 26. The Aerodyne 38 is 11.48 m long with a total sail area of 74 m² that achieve speeds of 7 m/s in apparent winds of at least 10 m/s while sailing in the beam reach mode.



Figure 26. Example of an Aerodyne 38, from [59]

The estimated costs of outfitting a used Aerodyne 38 into an energy-ship are displayed in Table 5. The ship board installed desalinators, electrolyzers and compressors will convert the electric power generated by the hydroturbine into hydrogen while the oxygen is vented overboard.

Component	Cost (USD)
Used Aerodyne 38 boat	125000
Hydroturbine (50 kW)	50000
Desalinator	2500
Electrolyser	21500
Hydrogen Compressor	15000
Hydrogen Storage Tank (20 kg)	14800
Total Cost	228800
OR	
Hydrogen Storage Tank (80 kg)	59200
Total Cost	273200

Table 5. Initial Energy Ship Cost Using Aerodyne 38

These preliminary cost estimates of the major components required by the energy ship concept show that the initial capital investment costs for a retrofitted boat capable of delivering 50 kW input power to an electrolyser would cost at least \$250,000. A 50 kWh electrolyser operation delivers approximately 1 kg of hydrogen per hour; therefore, 24kg of hydrogen can be produced in a 24hr operating period.

G. GRIMSEY ISLAND

Chade et al [47] conducted a study on the feasibility of providing power to a remote arctic location by converting wind energy to hydrogen. Grimsey Island is a small island of the northern coast of Iceland and has approximately 76 inhabitants and is shown in Figures 27 and 28.



Figure 27. Aerial View of Grimsey Island, from [60]



Figure 28. Geographic Location of Grimsey Island, from [61]

In their paper, they give the Grimsey Island average daily power requirements shown in Figure 29 in addition to stating that the PEM fuel cell unit used during the case study required $0.045 \text{ kg H}_2/\text{hr/kW}$.

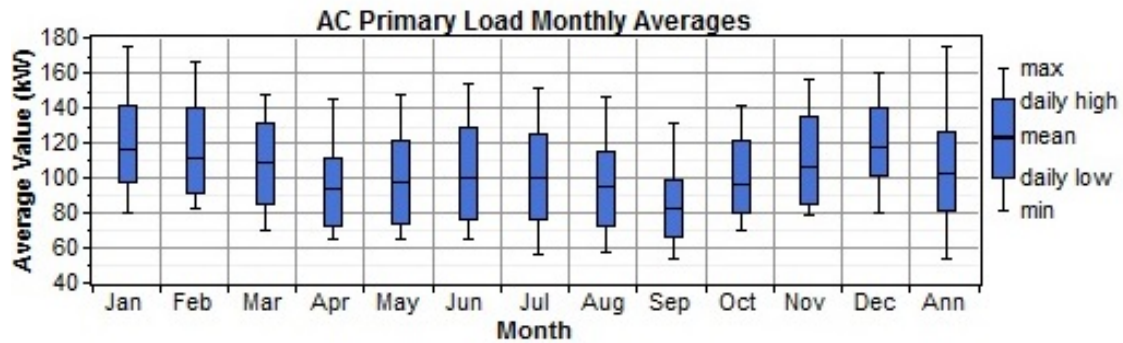


Figure 29. Grimsey Island Average Monthly Power Requirements, from [47]

The peak average power required by the inhabitants of Grimsey Island was roughly 120kW in January and the minimum average power required was 85kW in September. This implies that required amount of hydrogen varied from 130kg to 92kg which is calculated using the previously state fuel cell conversion rate.

They considered two methods to provide power to the inhabitants of Grimsey Island and their suggested wind-hydrogen-diesel system was the most cost effective. The cost of each component and the total cost of the power generation system are tabulated in Table 6.

Grimsey Island: Wind-Hydrogen-Diesel System	
Component	Cost (USD)
(3) Wind Turbines that produce 100 kW each	1,210,757
Diesel Generator	960,069
Electrolyser (150 kW)	271,569
Fuel Cell (150 kW)	246,901
Hydrogen Tank (250 kg)	185,117
Converter (200 kW)	150,000
Total Cost	3,024,413

Table 6. Component Cost for the Grimsey Island Wind-Hydrogen-Diesel System, after [47]

Chade et al [47] examined the relationship between the average monthly stored hydrogen, excess electrical production, and average monthly diesel generated electrical output and showed that there existed a need for hydrogen storage for least two weeks. Between January and February and from October to November Grimsey Island produced and stored an excess of 150 to 200kg of hydrogen. In June, it was observed that no excess power was generated and the diesel oil was needed in order to supplement the power requirements. It was shown that the implementation of this type of renewable energy system reduced required diesel oil consumption by 85 percent from the use of a purely diesel oil dependent system.

Chade et al. [47] also analyzed the possibility of using a pure wind-hydrogen system without the use of a supplemental diesel generator. This system would have required additional wind turbine generators and a larger electrolyser, converter, and an 850kg hydrogen storage tank. In addition to requiring additional and larger equipment, the estimated investment cost to

implement this method is different compared to the wind-hydrogen-diesel system. The cost to implement the wind-hydrogen system is shown in Table 7.

Grimsey Island: Wind-Hydrogen System	
Component	Cost (USD)
(7) Wind Turbines that produce 100 kW each	2,825,101
Electrolyser (300 kW)	543,138
Fuel Cell (150 kW)	224,498
Hydrogen Tank (850 kg)	629,399
Converter (300 kW)	225,000
Total Cost	4,447,136

Table 7. Component Cost for the Grimsey Island Wind-Hydrogen System, after [47]

The total cost for the wind hydrogen system was estimated to be 4.5 million USD. The excess electrical energy and required hydrogen storage increase significantly used this system. The average monthly stored hydrogen between October and May was 800kg.

V. ASSESSMENT OF THE POTENTIAL FOR RENEWABLE POWER SUPPLY FOR A HYPOTHETICAL NAVAL FACILITY

In the absence of specific information regarding the power requirements of an actual remote naval facility we assumed power requirements similar to the Grimsey Island case study. The feasibility of satisfying these power requirements by using energy ships, operating year-round, in ocean areas exposed to average annual wind speeds of 10 m/s was analyzed next. It was also either assumed that the these vessels would be operating sufficiently close to the naval facility in order to maintain the ability to offload their hydrogen storage tanks once a week or that the hydrogen storage tanks would be transferred to a separate transport vessel during an underway offloading which would allow the energy-ships to operate at considerable distances from the naval facility making unloading stops impractical.

The power requirements are assumed to be comparable to the Grimsey Island power consumption. It is assumed that 120kW and 85kW will respectively represent the maximum and minimum power required. In this analysis, a fuel cell conversion rate of 0.045 kg H₂/hr/kW is also assumed. This would imply that

$$120kW \times 0.045 \frac{kg H_2}{kW} \times 24 \frac{hr}{day} = 130 \frac{kg H_2}{day} ,$$

the energy-ship(s) will be required to produce 130kg H₂ in order to completely support the naval facility.

Ideally, it will be preferable to design, construct and demonstrate an energy ship that is specifically tailored for the mission of operating in high-wind ocean areas (with winds of 10 m/s or more) for extended periods of time. The design of this vessel would have to maximize the available sail area and minimize the ship's overall resistance or drag. The most practical ship configuration is likely to be a catamaran or trimaran hydrofoil boat whose sail area would likely be augmented by a parawing. However, the design,

development and testing costs of such a project would be quite high and beyond the scope of this analysis. Therefore, to determine if further investigation into this matter is even justified, it is more appropriate to examine the feasibility of retrofitted available vessels into energy-ships capable of meeting the required power demands of the hypothetical remote naval facility.

Analyzing the data represented in Figures 20 to 25 shows that the generation of 25 kW to 50 kW requires sail areas between 70 to 200 m² depending on wind conditions, wetted area, and sail lift coefficient; therefore, the generation of power in the realm of 25kW is obtainable by using a typical sailing craft. The Aerodyne 38 and Catalina 36 are two examples of sailing vessels that could meet the required sail area and are both single-hull vessels. The Aerodyne 38 is 11.48m long, has a beam width of 4m, and a total sail area of 74 m². The CATALINA 36 MK II, shown in Figure 30, is 11m long, has a beam width of 3.63 m, and a total sail area of 52 m².

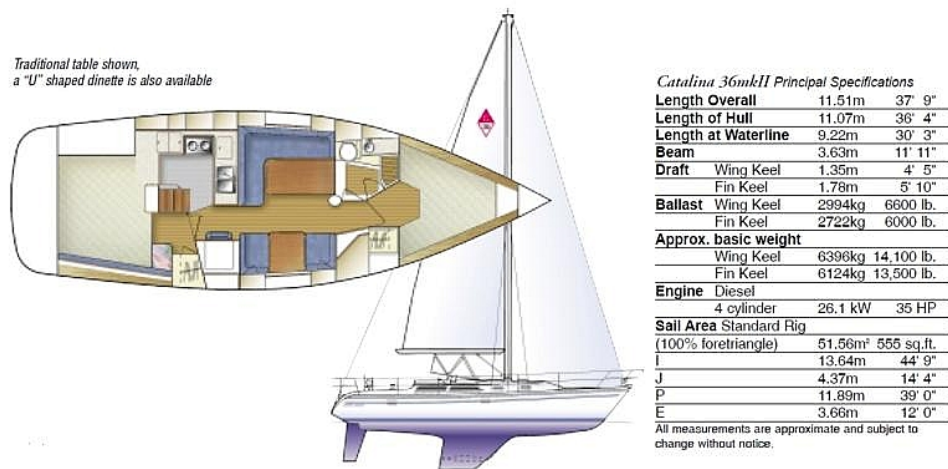


Figure 30. Example of a Catalina 36, from [62]

Since the Catalina 36 has less sail area than required and the Aerodyne 38 has approximately the minimum sail area required for the generation of 25kW, it is within the realm of possibilities to lengthen the mast in order to accommodate additional sail area or to accommodate the addition of a parawing. Used

Aerodyne 38 boats and Catalina 36 boats are advertised for sale at \$125,000 and \$40,000, respectively. Both sale prices are a representation of lowest cost values in order to demonstrate a rough minimum cost for the retrofit endeavor.

The project feasibility and cost analysis will be based on the CATALINA 36 boat. The required sail area for a power output of 20 kW is shown in Figures 31–34. It is seen that the sail area needs to be doubled for sail lift coefficients of 1.75 and wind speeds of 10 m/s. Reducing the wind speed to 8 m/s requires a considerable increase in sail area. On the other hand, increasing the sail lift coefficient is quite beneficial. The ship's wetted area significantly affects the required sail area and it is shown in Figure 34, that a reduction of the wetted area from 50 to 5 or even to 10 m², by means of hydrofoils, makes it possible to generate 20 kW with the existing sail area of 50 m². Analysis of the data suggests that equipping a CATALINA 36 boat with either a parawing or hydrofoils enables the production of 20 kW electrical power for the production of 10kg of hydrogen per day. Speculation of the addition of both a hydrofoil platform and a parawing, to increase sail area, should make it possible to produce well in excess of 20 kW. Furthermore, as documented in previous sections, the space and weight requirements for the desalinators, electrolyser, compressor and hydrogen tank can be met without significant difficulties.

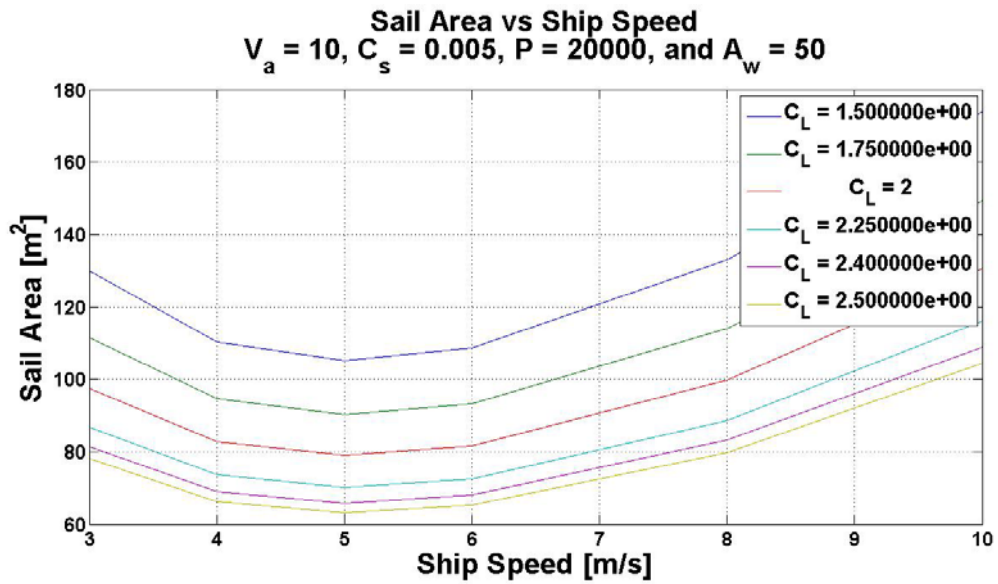


Figure 31. Sail Area versus Ship Speed with Variable Sail Lift Coefficient and Power Set to 20000 Watts

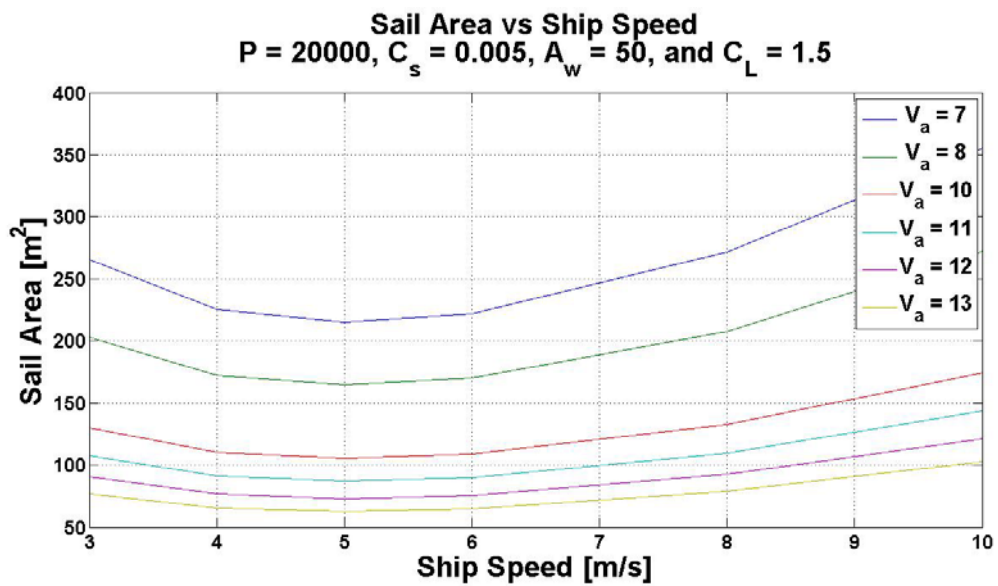


Figure 32. Sail Area versus Ship Speed with Variable Apparent Wind Speed and Power Set to 20000 Watts

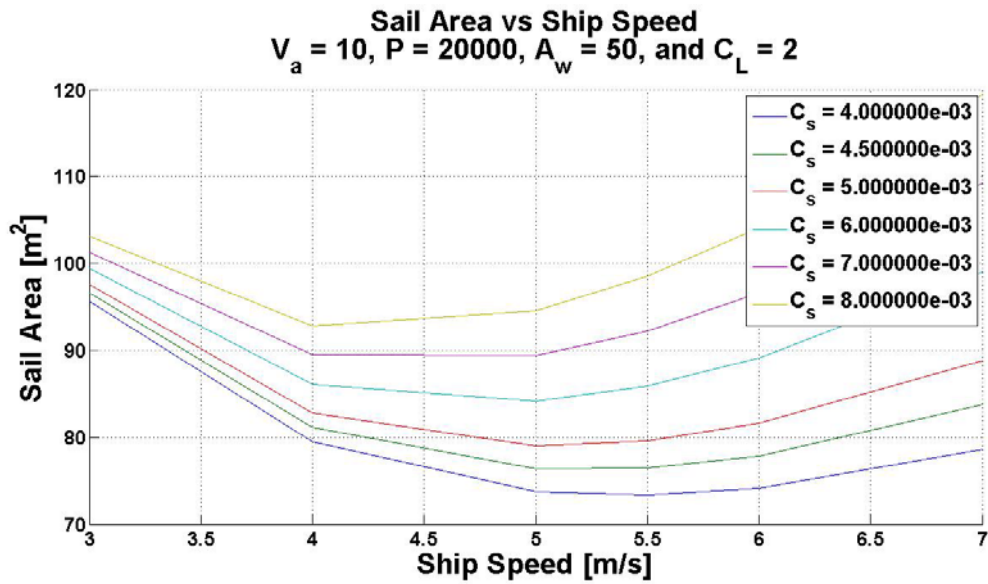


Figure 33. Sail Area versus Ship Speed with Variable Ship Drag Coefficient and Power Set to 20000 Watts

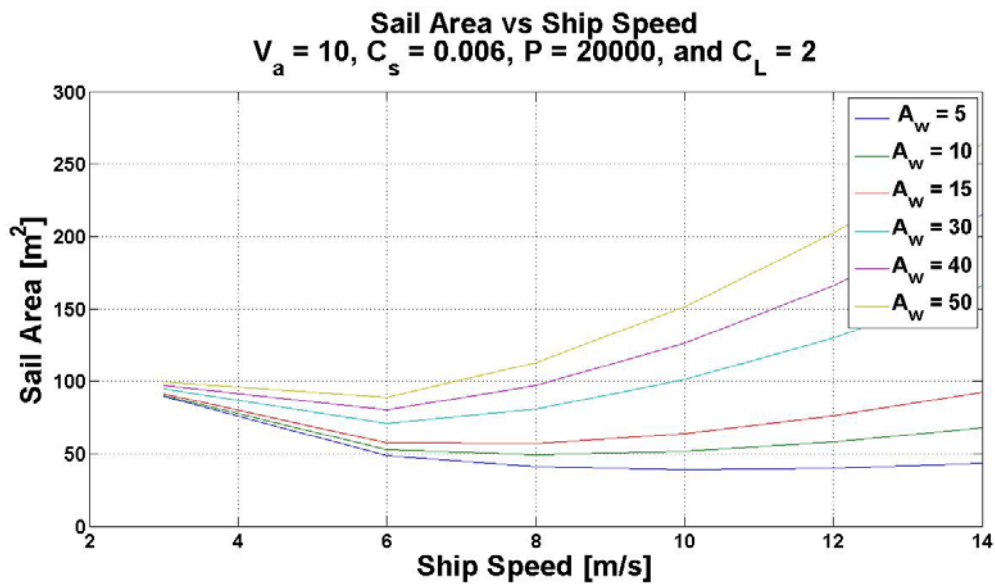


Figure 34. Sail Area versus Ship Speed with Variable Ship Wetted Area and Power Set to 20000 Watts

The total investment costs required retrofitting a Catalina 36 into an energy-ship equipped with a 20kW hydroturbine and a parawing is shown in Table 8.

Component	Cost (USD)
Used Catalina 36	40,000
Parawing	10,000
Hydroturbine (20 kW)	30,000
Desalinator	2,500
Electrolyser	17,000
Hydrogen Compressor	10,000
Hydrogen Storage Tank	60,000
Total Cost	169,500

Table 8. Initial Energy Ship Cost using Catalina 36
Equipped with Parawing

The SAGIM BP-MP1000/5000 electrolyser was selected because it is rated to produce a maximum of 5 Nm³ H₂/hr or 10.79 kg H₂/day. The Hydrogencis HYSTAT 10 electrolyser, which is capable of yielding 8.6 to 21.5kg H₂/day, could have also been used. In order to attempt to maximize storage capacity and minimize weight the Dyneteck hydrogen storage tank is estimated to cost \$59,200 and can hold 80kg H₂. It will be necessary for the energy-ships to offload once a week if it is assumed that they are producing 10.79kg H₂/day and have a storage capacity of 80kg.

Based on the anticipated H₂ production rate it will be required to operate thirteen energy-ships continuously in order to provide the required 130kg H₂ to the hypothetical naval facility. The estimated total cost for thirteen energy-ships is \$2,203,500 if the estimated cost per ship is \$169,500 as seen from Table 5. This shows that the energy-ship concept is cost competitive with the wind-hydrogen-diesel method that was analyzed for the Grimsey Island study presented by Chade et al. [47]. This rough estimate implies that the energy-ship concept would cost 0.5 million USD less to implement and provide continuous renewably supplied power to a small and remote naval facility.

This analysis and potential cost estimate are preliminary and are based on several assumptions that will require a further detailed analysis. This cost estimate assumes that each ship can be procured for \$50,000 or less and it also negates the potential cost for a transport vessel if one is required depending on the operating distance from the vessel's homeport. This analysis is also assuming an autonomously operated sailing vessel similar to Saildrone 1 (SD1). The analysis done on the energy-ship concept demonstrated its economic competitiveness with traditional power generation methods regardless of the assumptions stated.

The analysis was completed in order to determine whether the energy-ship concept could provide the required power to a hypothetical naval facility in a direct comparison with the analysis conducted by Chade et al. [47] in the Grimsey Island case study. It was seen during the Grimsey Island case study that there was a sufficient amount of excess energy generated and stored as hydrogen when they analyzed the implementation of the wind-hydrogen system. This same situation could be encountered for hydrogen generation using the energy-ship concept. Therefore, the possible use of excess hydrogen for transportation purposes can be speculated upon. The Technology Transition Corporation states, in its 2010 U.S. Market Report, that the price at the pump for hydrogen might be \$6–12 per kg. However, one kilogram of hydrogen has the same amount of energy as a gallon of gasoline; therefore, a vehicle can be driven twice as far on 1 kg H₂ compared to a gallon of gasoline which implies that the cost is equivalent to \$3–6 per gallon of gasoline [16].

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VI. SUMMARY AND RECOMMENDATIONS

This thesis analyzed whether it is technically and economically feasible to deliver hydrogen to a small remote naval facility in order to meet the facility's power requirements. The delivered hydrogen would be converted into electrical power by use of fuel cells or it could be used for transportation, cooking, and heating purposes. It was assumed that the power demand could be met by the generation of 130kg H₂ per day. The hydrogen production method was based on the "energy-ship concept" where sailboats are used in wind-rich ocean areas that experience average sustained wind speeds of 10m/s and greater. These sustained high wind speeds would facilitate average vessel cruising speeds of approximately 6m/s. The boats are equipped with hydrokinetic turbines for the purpose of feeding electrical power into electrolyzers that will convert sea water into hydrogen and oxygen. The hydrogen is then compressed, stored, and subsequently delivered to a naval facility for distribution and use.

By estimating the associated drag of the boat and turbine, the turbine power output, the sail lift, the potential power requirements of the desalinator, electrolyser and hydrogen compressor it was shown that boats with 50 to 80 m² sail area could generate 20kW power. The Catalina 36 and Aerodyne 38 were chosen as two examples that possessed the approximate sail area. The correct parameters necessary to generate 20kW could more confidently be obtained if the chosen vessel were augmented with a parawing or equipped with hydrofoils to reduce the drag. It was also concluded that an energy-ship that produced 20kW could generate approximately 10kg H₂ per day which implies that a fleet of 13 vessels would be required to generate the needed 130kg H₂ per day.

The economics of this type of hydrogen production was evaluated by estimating the total costs required for retrofitting the 13 vessels with the necessary equipment and comparing them with the cost analysis performed in the Grimsey Island case study. It was established that hydrogen production by use of the energy-ship concept was cost competitive and provided an economic

alternative for the wind-hydrogen system proposed for Grimsey Island. This is assuming that the vessels are operating autonomously to minimize personnel cost required for project operation.

Additional work and analysis is still required since this was a preliminary analysis in order to determine the economic feasibility and cost competitiveness of the energy-ship concept as a viable alternative to traditional fossil fuel sources. A large percentage of the future work will have concentrate on proceeding from the conceptual energy-ship design to the preliminary design phase. This phase should focus on a more thorough cost estimate of the various components comprising the energy ship concept. Another point of interest is the potential of designing a mission specific vessel. The analysis of designing a mission specific vessel would determine the cost benefit of attempting to increase the sail area in addition to minimizing the drag of the vessel. This investigation would look at the potential of designing vessels with 500m², 1000 m² or even 5000m² sail areas in addition to the adoption of a hydrofoil platform.

It is important to remember that the energy-ship produces both oxygen and hydrogen. Therefore, there is need for further work to determine whether there is an economic benefit in storing and selling or using the generated oxygen as well. Furthermore, electrical power generation in a hydrogen fuel cell generates water as a waste byproduct. Large-scale hydrogen production operations, using the energy-ship concept, have the additional benefit of producing significant amounts of water which could be used on the naval facility or stored for use during disaster response or humanitarian aid missions.

Finally, the use of hydrogen is, potentially, not only limited as a fuel source for land and sea transportation purposes. While its practicality for direct use in airplanes is questioned by most airplane propulsion experts, hydrogen can be transformed into methanol by reacting it with carbon dioxide. This makes it possible to develop environmentally neutral aircraft propulsion systems assuming that the carbon dioxide is being generated from conventional carbon-based power plants.

APPENDIX A. MATLAB CODE: SENSITIVITY ANALYSIS

```
% -----
% Paradis, Jason
% Parameter Sensitivity Analysis For Hydrogen Ship Concept
% -----
clc
clear all
close all
% -----
% Constants
% rho_w is the density of water [kg/m^3]
% C_t is the turbine drag coefficient
% C_p is the turbine power coefficient
% rho_a is the density of air [kg/m^3]
% -----
rho_w = 1000;
C_t = 2;
C_p = 1.26;
rho_a = 1.2;
parameters = [rho_w C_t C_p rho_a];
% -----
% Variables
% The following are the parameters which are to be varied in order to
% evaluate the sensitivity and relationship between parameters.
%
% V_w is the velocity of the ship [m/s]
% C_s is the ship's drag coefficient
% A_w is the ship's wetted area [m^2]
% P is the power output of the turbine [W]
% V_a is the apparent wind speed [m/s]
% C_L is the sail lift coefficient
% -----

% -----
% The following variables can either be entered in manually allowing % the user
% to specify specific values or N can be varied which will % utilize the linspace
% command to specify the quantity of values to % examine within the specified
% boundaries. The equation n = numel(A_w) % is used in both cases to feed an
% iteration number into the for loops % used to calculate the sail area in all cases.
% -----
A_w = [5 10 15 20 25 30];
C_s = [0.004 0.0045 0.005 0.006 0.007 0.008];
V_a = [8 10 11 12 13 15];
```

```

C_L = [1.5 1.75 2 2.25 2.4 2.5];
V_w = [3 5 8 10 12 14];
P = [20000 30000 35000 40000 45000 50000];
% N = 10; % N is the number of values within the boundary of each parameter
%
% A_w = linspace(5,300,N);
% C_s = linspace(0.004,0.006,N);
% V_a = linspace(6,20,N);
% C_L = linspace(1.0,3.0,N);
% V_w = linspace(4,30,N);
% P = linspace(50000,200000,N);
n = numel(A_w);
%-----
for i = 1: n
    for j = 1: n
        for k = 1 : n
            for h = 1 : n
                for l = 1: n
                    for m = 1: n
                        A_s( (( (i-1)*(n^4)) + ( (j-1)*(n^3) ) +...
                            ( (k-1)*(n^2)) + ((h-1)*n) + l), m) =...
                            ( 0.5*rho_w*((V_w(i))^2)*(C_s(j)) ...
*(A_w(k))+((C_t/C_p) * ((P(h))/ ...
(V_w(i))) ) )/ (0.5*rho_a* ...
((V_a(l))^2)*C_L(m));
                    end
                end
            end
        end
    end
end
end

% -----
% The variable parameters are designated as follows:
% m = C_L (Sail Lift Coefficient)
% l = V_a (Apparent Wind Speed)
% h = P (Turbine Power Output)
% k = A_w (Ship's Wetted Area)
% j = C_s (Ship's Drag Coefficient)
%
% The ship's speed (V_w) will be varied in all calculations.
% -----
j = 4; jj = num2str(C_s(j));
k = 4; kk = num2str(A_w(k));
h = 1; hh = num2str(P(h));

```

```

l = 2; ll = num2str(V_a(l));
m = 3; mm = num2str(C_L(m));
% -----
% The below code calls the function sail_area and inputs the variables
% corresponding to the above conditions of m, l, h, k, and j which
% represent a specific value from within the bounds of each variable.
% The sail_area outputs a single point representing sail area for the % input
% parameters which can be used to verify the results from the % code used to
% graph results of ship's speed versus sail area while % varying a second
% parameter.
% -----
X = [C_s(j) A_w(k) P(h) V_a(l) C_L(m)];
Sail_area = sail_area(parameters,X,V_w);
% -----
% Letting i = 1:n will vary the ship's speed through all values as % defined
% above.
% -----

clr = lines(n); % Specifies a 6x3 matrix that refers to a 'lines'
colormap
z1 = zeros(n,1);
z2 = zeros(n,1);
z3 = zeros(n,1);
z4 = zeros(n,1);
A_s_plot = ones(1,n);

% -----
% The below code plots ship's speed versus sail area while varying the
% ship's drag coefficient (C_s).
for j1 = 1:n;
for i = 1:n
A_s_plot(i) = A_s(l+((h*n)-n)+((k*(n^2))-(n^2))+((j1*(n^3))-(n^3))+
((i*(n^4))-(n^4)),m);
end
hold on
figure(1)
z1(j1)= plot(V_w,A_s_plot,'LineStyle','-', 'Color',clr(j1,:));
end

set(gca,'Fontweight','b','FontSize',18);
xlabel('Ship Speed [m/s]','FontSize',26);
ylabel('Sail Area [m^2]','FontSize',26);
title(['Sail Area vs Ship Speed', ['V_a = ',ll, ', P = ', hh,...
', A_w = ',kk, ', and C_L = ',mm]], 'FontSize',26);
grid on

```



```

h_legend = legend(z1,num2str(C_s(1:n)'),'C_s = %d')
set(h_legend,'FontSize',20)
% -----

% -----
% The below code plots ship's speed versus sail area while varying the
% apparent wind speed (V_a).
for l1 = 1:n;
for i = 1:n
A_s_plot(i)    =    A_s(l1+((h*n)-n)+((k*(n^2))-(n^2))+((j*(n^3))-(n^3))+((i*(n^4))-(
(n^4)),m);
end

hold on
figure(2)
    z2(l1)= plot(V_w,A_s_plot,'LineStyle','-','Color',clr(l1,:));
end

set(gca,'Fontweight','b','FontSize',18);
xlabel('Ship Speed [m/s]','FontSize',26);
ylabel('Sail Area [m^2]','FontSize',26);
title(['Sail Area vs Ship Speed','P = ', hh, ', C_s = ', jj,...
    ', A_w = ',kk, ', and C_L = ',mm]','FontSize',26);
grid on
h_legend = legend(z2,num2str(V_a(1:n)'),'V_a = %d')
set(h_legend,'FontSize',20)
% -----

% -----
% The below code plots ship's speed versus sail area while varying the
% turbine output power (P).

for h1 = 1:n;
for i = 1:n
A_s_plot(i)    =    A_s(l+((h1*n)-n)+((k*(n^2))-(n^2))+((j*(n^3))-(n^3))+((i*(n^4))-(
(n^4)),m);
end
    hold on
    figure(3)
        z3(h1)= plot(V_w,A_s_plot,'LineStyle','-','Color',clr(h1,:));
end

set(gca,'Fontweight','b','FontSize',18);
xlabel('Ship Speed [m/s]','FontSize',26);
ylabel('Sail Area [m^2]','FontSize',26);

```

```

title({'Sail Area vs Ship Speed',[ 'V_a = ', ll, ' ', C_s = ', jj,...
    ' ', A_w = ',kk, ' ', and C_L = ',mm]], 'FontSize',26);
grid on
h_legend = legend(z3,num2str(P(1:n)'),'P = %d')
set(h_legend,'FontSize',20)
% -----

% -----
% The below code plots ship's speed versus sail area while varying the
% ship's wetted area (A_w).
for k1 = 1:n;
    for i = 1:n;
        A_s_plot(i) = A_s(l+((h*n)-n)+((k1*(n^2))-(n^2))+((j*(n^3))-(n^3))+((i*(n^4))-
            (n^4)),m);
        end
        hold on
        figure(4)
        z4(k1)= plot(V_w,A_s_plot,'LineStyle','-','Color',clr(k1,:));
    end

set(gca,'Fontweight','b','FontSize',18);
xlabel('Ship Speed [m/s]','FontSize',26);
ylabel('Sail Area [m^2]','FontSize',26);
title({'Sail Area vs Ship Speed',[ 'V_a = ', ll, ' ', C_s = ', jj,...
    ' ', P = ', hh, ' ', and C_L = ',mm]], 'FontSize',26);
grid on
h_legend = legend(z4,num2str(A_w(1:n)'),'A_w = %d')
set(h_legend,'FontSize',20)
% -----

% -----
% The below code plots ship's speed versus sail area while varying the
% ship's lift coefficient (C_L).

for m1 = 1:n;
    for i = 1:n;
        A_s_plot(i) = A_s(l+((h*n)-n)+((k*(n^2))-(n^2))+((j*(n^3))-(n^3))+((i*(n^4))-
            (n^4)),m1);
        end
        hold on
        figure(5)
        z5(m1)= plot(V_w,A_s_plot,'LineStyle','-','Color',clr(m1,:));
    end

set(gca,'Fontweight','b','FontSize',18);

```

```

xlabel('Ship Speed [m/s]', 'FontSize', 26);
ylabel('Sail Area [m^2]', 'FontSize', 26);
title({'Sail Area vs Ship Speed', ['V_a = ', ll, ', C_s = ', jj, ...
    ', P = ', hh, ', and A_w = ', kk]}, 'FontSize', 26);
grid on
h_legend = legend(z5, num2str(C_L(1:n)), 'C_L = %d')
set(h_legend, 'FontSize', 20)
% -----

```

APPENDIX B. MATLAB CODE: SAIL AREA

```
% -----  
% Sail Area  
% A_s is the ship's sail area [m^2]  
% rho_w is the density of water [kg/m^3]  
% V_w is the velocity of the ship [m/s]  
% C_s is the ship's drag coefficient  
% D_t is the turbine drag [N]  
% rho_a is the density of air [kg/m^3]  
% V_a is the apparent wind speed [m/s]  
% C_L is the sail lift coefficient  
%  
% X = [C_s(j) A_w(k) P(h) V_a(l) C_L(m)];  
% -----  
  
function [A_s] = sail_area(parameters,X,V_w)  
rho_w = parameters(1);  
C_t = parameters(2);  
C_p = parameters(3);  
rho_a = parameters(4);  
  
A_s = ((0.5*rho_w.*V_w.^2.*X(1).*X(2))+((C_t/C_p)* ...  
(X(3)./V_w)))./(0.5*rho_a.*(X(4).^2).*X(5));  
end
```

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